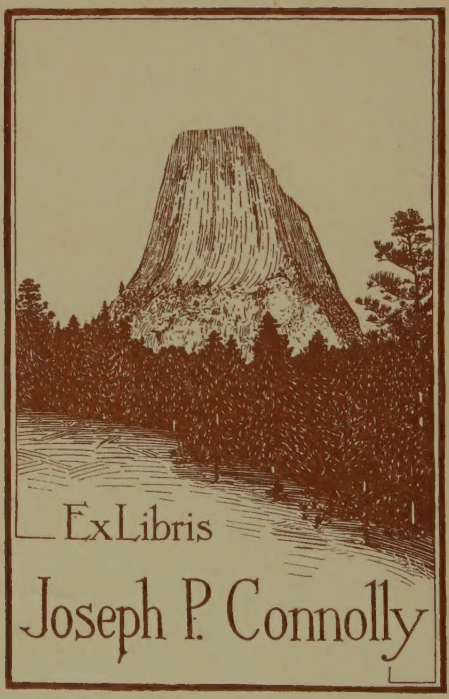
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INTRODUCTION TO THE STUDY OF MINERALS AND ROCKS

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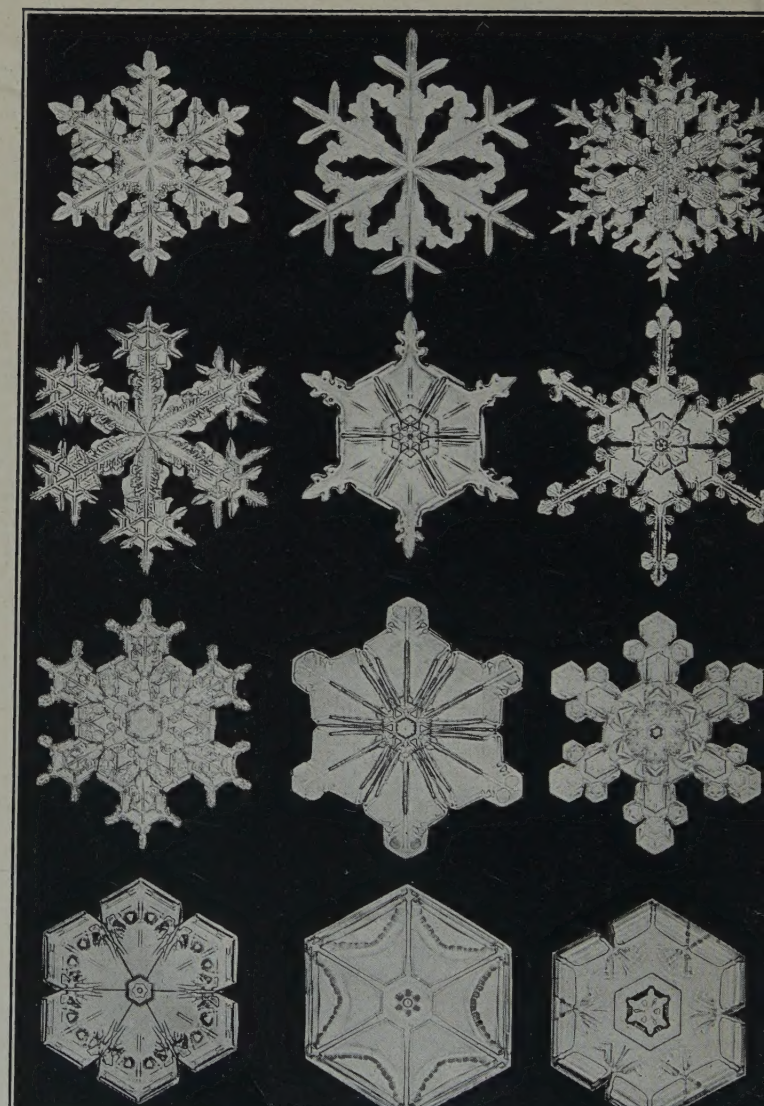

Microphotographs of snow cryst ls. (*After Bentley.*)

(*Frontispie*

INTRODUCTION TO THE STUDY OF MINERALS AND ROCKS

A COMBINED TEXT-BOOK AND POCKET MANUAL

BY

AUSTIN FLINT ROGERS, PH. D.

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PREFACE

This work is intended primarily as a text-book for a year's work in the study of minerals and rocks. While full enough for class work it is condensed enough for field work. There is decided advantage in using the same book in the field as in the class room and laboratory.

Part II contains the description of 175 minerals. These have been selected with great care, although the list is necessarily an arbitrary one based upon the author's experience and judgment. These include all the common minerals and most of those of any special economic, geological, or scientific importance. Some of the minerals are comparatively rare but are selected so as to give a comprehensive view of the mineral kingdom as a whole.

About a third of the more common and important of the minerals are distinguished by larger type than the others. These fifty-six minerals include all the very common minerals taken the world over. In a short course in mineralogy attention may be confined exclusively to the shorter list and in that case other portions of the book also would have to be disregarded.

The section dealing with the chemical properties of minerals has been placed first because in elementary work it is of prime importance. A qualitative scheme, especially applicable to minerals in that calcium phosphate, fluorid, and borate are provided for, has been included.

In geometrical crystallography, symmetry has been emphasized and the idea of hemihedrism is abandoned. A tabulation of the thirty-two crystal classes is given but only eleven of the thirty-two classes are described in detail. From one to four common minerals of each class are used as illustrations. Groth's

names of the thirty-two classes and Fedorov's names of forms are used. The Miller symbols have been used to the exclusion of all others. Plans and elevations of crystals are made much use of, for they furnish a convenient means of determining indices and axial ratios graphically. The section on the internal structure of crystals has been revised and augmented in the light of the work done by the Braggs and others in recent years.

Among the physical properties the optical properties are treated at some length because of their great value in the determination of minerals. The determination of the microscopic and optical properties of minerals in crushed fragments is emphasized. No one is properly equipped to determine minerals until he understands fairly well the subject of optical crystallography.

In Part II the order of the minerals is practically the same as that of Dana's *System of Mineralogy* except that the silicates are placed last. The silicates are the most difficult minerals and so they are reached after the student has gained considerable experience with the other groups. Some changes in the standard nomenclature of minerals may be mentioned. Bauxite is treated as a rock made up of the amorphous mineral cliachite and the crystalline mineral gibbsite. Serpentine is also considered a rock, its principal mineral being antigorite. Collophane, an amorphous calcium carbonophosphate is regarded as the chief constituent of phosphorite or so-called phosphate rock. It is also the mineral of fossil bones and so is a very widely distributed mineral. The amorphous minerals turyite, cliachite, collophane, and halloysite are the amorphous equivalents of the following crystalline minerals respectively, hematite, gibbsite, dahllite, and kaolinite. Natural glass and hydrocarbons are treated in an appendix to the minerals under the term mineraloid.

In Part III there is an elementary discussion of the occurrence, association, and origin of minerals. This includes a brief description of some of the more common and important rock types and also of the prominent classes of veins and replacement deposits.

Appended to Part IV there are two tables for the determination of minerals. In the first the principal dependence is upon crystal form and physical properties and so it may be used in the field as well as in class room. In using Table II the mineral is determined mainly by finding its constituent acid radicals and metals by chemical and blowpipe tests and so its use is confined to the laboratory. If a polarizing microscope is available, optical and microscopic tests will greatly aid in the identification of minerals. The table on page 192 may be used to advantage.

A glossary of terms not explained in the text has been included with the index. Synonyms and varieties are usually given in the glossary rather than in the text.

Thanks are due my colleague, Professor C. F. Tolman, Jr., for suggestions concerning certain portions of Part III. I am also indebted to my daughter, Genevieve Rogers, for assistance in reading proof.

A. F. R.

Stanford University.

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INTRODUCTION TO THE STUDY OF MINERALS AND ROCKS

INTRODUCTION

A mineral may be defined as a naturally occurring homogeneous, inorganic substance of definite or fairly definite chemical composition and with characteristic physical properties. Minerals are to a large extent the units which make up the rocks of the earth's crust or outer shell. Many of them are useful to man. A knowledge of minerals is obviously necessary to the geologist and to some extent to the engineer, the chemist, and the metallurgist.

About a thousand definite minerals are well established but many of them are very rare and have been found at but a single locality. Only about two hundred or so are of much importance from either a geological or economic standpoint.

The information concerning minerals may be conveniently placed under two general heads: (1) the properties of minerals and (2) the relations of associated minerals.

The properties of minerals naturally divide themselves in three groups: (1) chemical, (2) morphological, and (3) physical. The morphological properties, or those concerned with external form and internal structure, form a connecting link between the other two.

The most fundamental fact about a mineral is its chemical composition. Many minerals have a definite chemical composition; for all minerals it is definite within certain limits. The classification of minerals is primarily a chemical one. For sight recognition the morphological and physical properties are very important, but for the purposes of exact identification it is often necessary and always advisable to make a more or less

complete chemical examination of the mineral. Wet tests must often be resorted to, but the blowpipe is very useful in the determination of the chemical composition of a mineral. For these reasons inorganic chemistry is the important prerequisite for the study of mineralogy.

The great majority of minerals when produced under favorable conditions assume the geometric forms called crystals and these forms are characteristic as in the case of plants and animals. An elementary knowledge of crystallography is essential in the study of minerals, for it must be emphasized that chemical composition alone does not define a mineral. Many chemical elements and compounds occur in two or more distinct forms which are known as polymorphs. We have, for example, calcium carbonate in two well-defined forms: calcite and aragonite. Although these have exactly the same chemical composition, they are distinct minerals, for they each have a distinctive crystal form and distinctive physical properties such as cleavage and specific gravity.

Another reason for studying crystallography is the ease of identification of many minerals by their crystal form alone. Again, a knowledge of crystal morphology is essential to a proper understanding of physical properties because there is an intimate relation between the crystal form and physical properties.

The physical properties of minerals are important because the external crystal form is often lacking. The external form, however, is the result of an internal structure and the internal structure is reflected in the physical properties. A few of the physical properties, such as the specific gravity, are independent of the direction (scalar properties), but most of them depend upon the crystallographic direction and so are called vectorial. Of all the vectorial properties, the optical properties are the most important in the description and determination of minerals. The polarizing microscope may be used to determine practically all of the optical properties. This method has a great advantage over chemical methods in that a very small quantity of material suffices and

also because two or more substances may be recognized in the presence of each other.

The chemical, morphological, and physical properties are of practically equal importance. One is very much handicapped if he neglects any one of these three groups.

After the properties of a mineral are ascertained and the mineral determined, there yet remain the facts of its occurrence and association, and the problem of its origin. The rôle that the mineral plays in nature is fully as important and interesting as the properties of the mineral. This is probably the most fascinating branch of mineral science. It includes not only the study of rocks but also the study of mineral deposits in general, among which ore-deposits are prominent. The occurrence of certain minerals in certain rocks and mineral deposits is characteristic, and the mineral associations are more or less typical.

PART I

THE PROPERTIES OF MINERALS

THE CHEMICAL PROPERTIES OF MINERALS

A. CHEMICAL PRINCIPLES

As minerals are naturally occurring substances of more or less definite chemical composition, a knowledge of inorganic chemistry is the foundation of the student's work in mineralogy. While it is true that a few physical tests often serve to identify a mineral, a more or less complete chemical analysis is frequently necessary. It is also advisable to check the physical tests by a chemical examination. Minerals are the original sources of the chemical elements and compounds, with the exception of carbon and its various compounds which are obtained largely from plant and animal products. Mineralogy then may be regarded as the natural history branch of inorganic chemistry.

1. ELEMENTS

With the possible exception of some inert gases of the atmosphere (argon, krypton, neon, and xenon), all of the eighty-three known elements occur in minerals. Some are exceedingly rare and confined to one or two minerals, while others are very common and widely distributed in minerals. The following table of the elements with their symbols and atomic weights shows to some extent their occurrence in minerals.

Of the eighty-three elements enumerated, only about twenty occur as minerals in the free or uncombined state. They are carbon, sulfur, selenium, tellurium, arsenic, antimony, bismuth, mercury, copper, silver, gold, lead, iron, nickel, platinum, palladium, iridium, osmium, tantalum, and tin. This leaves out of

Table of Elements with their Atomic Weights
(International Committee, 1920–21)

Element	Symbol	Atomic weight	Occurrence
Aluminum	Al	27.1	Corundum, Al_2O_3
Antimony	Sb	120.2	Stibnite, Sb_2O_3
Argon	A	39.9	In the atmosphere
Arsenic	As	74.96	Arsenopyrite, FeAsS
Barium	Ba	137.37	Barite, $BaSO_4$
Beryllium (= Glucinum)	Be	9.1	Beryl, $Be_3Al_2(SiO_3)_6$
Bismuth	Bi	208.0	Bismuthinite, Bi_2S_3
Boron	B	10.9	Colemanite, $Ca_2B_6O_{11}.5H_2O$
Bromin	Br	79.92	Bromyrite, AgBr
Cadmium	Cd	112.40	Greenockite, CdS
Calcium	Ca	40.07	Calcite, $CaCO_3$
Carbon	C	12.005	Graphite, C
Cerium	Ce	140.25	Monazite, $(Ce, La)PO_4$
Cesium	Cs	132.81	Pollucite, $H_2Cs_2Al_2(SiO_3)_5$
Chlorin	Cl	35.46	Halite, NaCl
Chromium	Cr	52.0	Chromite, $(Fe, Mg)(Cr, Al)_2O_4$
Cobalt	Co	58.97	Smaltite, $(Co,Ni)As_2$
Copper	Cu	63.57	Chalcopyrite, $CuFeS_2$
Dysprosium	Dy	162.5	With the rare earths
Erbium	Er	167.7	Sipylite, $ErNbO_4$
Europium	Eu	152.0	With the rare earths
Fluorin	F	19.0	Fluorite, CaF_2
Gadolinium	Gd	157.3	In gadolinite
Gallium	Ga	70.1	In sphalerite
Germanium	Ge	72.5	Argyrodite, Ag_8GeS_6
Gold	Au	197.2	Gold, Au
Helium	He	4.00	In uraninite
Holmium	Ho	163.5	In gadolinite
Hydrogen	H	1.008	Water, H_2O
Indium	In	114.8	In sphalerite
Iodin	I	126.92	Iodyrite, AgI
Iridium	Ir	193.1	Iridosmine, (Ir,Os)
Iron	Fe	55.84	Hematite, Fe_2O_3
Krypton	Kr	82.92	In the atmosphere
Lanthanum	La	139.0	Lanthanite, $La_2(CO_3)_3.9H_2O$
Lead	Pb	207.20	Galena, PbS
Lithium	Li	6.94	Lepidolite, K,Li,Al silicate
Lutecium	Lu	175.0	With the rare earths
Magnesium	Mg	24.32	Magnesite, $MgCO_3$
Manganese	Mn	54.93	Pyrolusite, $MnO_2(H_2O)_4$
Mercury	Hg	200.6	Cinnabar, HgS
Molybdenum	Mo	96.0	Molybdenite, MoS_2
Neodymium	Nd	144.3	In monazite

Table of Elements with their Atomic Weights—*Continued*

Element	Symbol	Atomic weight	Occurrence
Neon	Ne	20.2	In the atmosphere
Nickel	Ni	58.68	Millerite, NiS
Niobium (= Columbium)	Nb	93.1	Columbite, $(Fe,Mn)(NbO_3)_2$
Niton	Nt	222.4	Radium emanation
Nitrogen	N	14.008	Nitratine, $NaNO_3$
Osmium	Os	190.9	Iridosmine, (Ir,Os)
Oxygen	O	16.00	Water, H_2O
Palladium	Pd	106.7	Palladium, Pd
Phosphorus	P	31.04	Apatite, $Ca_5F(PO_4)_3$
Platinum	Pt	195.2	Platinum, Pt
Potassium	K	39.10	Sylvite, KCl
Praseodymium	Pr	140.9	In monazite
Radium	R	226.0	In uraninite
Rhodium	Rh	102.9	In platinum
Rubidium	Rb	85.45	In rhodizite
Ruthenium	Ru	101.7	Laurite, RuS_2
Samarium	Sa	150.4	In samarskite
Scandium	Sc	45.0	In euxenite
Selenium	Se	79.2	Clausthalite, PbSe
Silicon	Si	28.3	Quartz, SiO_2
Silver	Ag	107.88	Argentite, Ag_2S
Sodium	Na	23.00	Halite, NaCl
Strontium	Sr	87.63	Celestite, $SrSO_4$
Sulfur	S	32.06	Sulfur, S
Tantalum	Ta	181.5	Tantalite, $Fe(TaO_3)_2$
Tellurium	Te	127.5	Calaverite, $AuTe_2$
Terbium	Tb	159.2	In gadolinite
Thallium	Tl	204.0	Lorandite, $TlAsS_2$
Thorium	Th	232.15	Thorite, $ThSiO_4$
Thulium	Tm	168.5	In gadolinite
Tin	Sn	118.7	Cassiterite, SnO_2
Titanium	Ti	48.1	Rutile, TiO_2
Tungsten	W	184.0	Wolframite, $(Fe,Mn)WO_4$
Uranium	U	238.2	Uraninite, U_3O_8
Vanadium	V	51.0	Vanadinite, $Pb_5Cl(VO_4)_3$
Xenon	Xe	130.2	In the atmosphere
Ytterbium	Yb	173.5	In gadolinite
Yttrium	Y	89.33	Xenotime, YPO_4
Zinc	Zn	65.37	Sphalerite, ZnS
Zirconium	Zr	90.6	Zircon, $ZrSiO_4$

consideration the free gases of the atmosphere. From a chemical standpoint the elements may be divided into two classes: the metals and the non-metals. The metals include such elements as

copper, silver, gold, lead, iron, and platinum. Some of these occur as alloys, such as electrum (Au,Ag), amalgam (Ag,Hg), nickel-iron (Fe,Ni), and iridosmine (Ir,Os). The non-metals include such elements as oxygen, hydrogen, nitrogen, phosphorus, and sulfur. Arsenic, antimony, and bismuth are intermediate in their properties between metals and non-metals, and hence are usually called semi-metals or metalloids.

2. CHEMICAL COMPOUNDS

Most minerals are, of course, chemical compounds, or combinations of two or more elements. These compounds are the chemical types recognized by chemists, namely: oxids, acids, bases, and salts, with their various subdivisions.

Acids are compounds, the dilute water solutions of which contain hydrogen ions. According to the theory of ions, it is the hydrogen ions that give the acid properties such as sour taste and the change of blue litmus to red. The strength of the acid depends upon the proportion of hydrogen ions present or upon the degree of dissociation. Hydrochloric and sulfuric acids are strong acids, while carbonic and silicic acids are weak acids. Acids are compounds of hydrogen with the halogens (Cl, Br, I, or F), with sulfur, or with certain radicals, such as CO_3, SO_4, PO_4, AsO_4, AsS_3, AsS_4, SbS_3, SbS_4. These are called **acid radicals.** The most common acids are those containing oxygen and hence are known as oxygen acids or oxy-acids. The oxy-acids are monobasic (HNO_3), dibasic (H_2SO_4), tribasic (H_3PO_4), or tetrabasic (H_4SiO_4), according as they have one, two, three, or four replaceable H atoms. The polybasic acids, as they are called, are capable of forming condensed acids by subtracting water. This is especially prominent with the silicic acids. Orthosilicic acid is H_4SiO_4; $H_4SiO_4 - H_2O = H_2SiO_3$, metasilicic acid; $2H_4SiO_4 - H_2O = H_6Si_2O_7$, diorthosilicic acid; $2H_2SiO_3 - 3H_2O = H_2Si_2O_5$, dimetasilicic acid. There are also $H_4Si_3O_8$ ($3H_4SiO_4 - 4H_2O$), $H_8Si_3O_{10}$ ($3H_4SiO_4 - 2H_2O$), and still other possible silicic acids.

The replacement in the oxy-acids of O by S gives compounds called **sulfo-acids.** Thus H_3AsO_4 is arsenic acid or oxy-arsenic acid, while H_3AsS_4 is sulfarsenic acid. H_3AsO_3 is arsenious acid, while H_3AsS_3 is sulfarsenious acid. Various condensed acids, which are entirely analogous to the condensed oxy-acids, are derived from the above by the subtraction of H_2S. Thus we have $HAsS_2(H_3AsS_3 - H_2S)$, metasulfarsenious acid, and $H_4As_2S_7$ $(2H_3AsS_3 - H_2S)$, pyrosulfarsenious acid. Very few of these acids exist either as minerals or prepared compounds, but salts of all of them are known as minerals.

Bases are compounds the dilute water solutions of which contain hydroxyl (OH) ions. The hydroxyl ions give the basic properties such as soapy feel, and the change of red litmus to blue. The strength of the base is proportional to the number of hydroxyl ions present. The strong bases such as KOH and NaOH are called alkalies. Weak bases are represented by $Fe(OH)_3$ and $Al(OH)_3$. Among the bases represented by minerals are $Mg(OH)_2$, $Mn(OH)_2$, $Al(OH)_3$, $HAlO_2[Al(OH)_3 - H_2O]$, and $HFeO_2[Fe(OH)_3 - H_2O]$.

Oxids are compounds of the elements with oxygen. Elements the oxids of which form bases with water are called metals. These oxids are called **basic anhydrids** for this reason. Elements the oxids of which form acids with water are called non-metals. These oxids are called **acid anhydrids.**

Salts are compounds formed by the union of bases with acids; the metal of the base unites with the non-metal or acid radical of the acid to form the salt, while the hydroxyl of the base unites with the hydrogen of the acid to form water thus: $NaOH + HCl = NaCl + H_2O$. In dilute solutions salts are dissociated into two parts or ions as they are called. The metal forms one ion, called the cation, while the non-metal or acid radical forms the other ion, called the anion.

Among salts we may distinguish halogen salts, oxy-salts, and sulfo-salts corresponding to the acids of which they are the derivatives. The following represent **salts found as minerals:**

Sulfid, PbS (galena).
Selenid, PbSe (clausthalite).
Tellurid, PbTe (altaite).
Arsenid, $FeAs_2$ (löllingite).
Antimonid, Ag_3Sb (dyscrasite).
Sulfarsenite Ag_3AsS_3 (proustite).
Sulfarsenate Cu_3AsS_4 (enargite).
Sulfantimonite Ag_3SbS_3 (pyrargyrite).
Sulfantimonate, Cu_3SbS_4 (famatinite).
Sulfoferrite, $CuFeS_2$ (chalcopyrite).
Sulfochromite, $FeCr_2S_4$ (daubreelite).
Sulfovanadate, Cu_3VS_4 (sulvanite).
Sulfogermanate, Ag_8GeS_6 (argyrodite).
Sulfostannite, $PbSnS_2$ (teallite).
Chlorid, AgCl (cerargyrite).
Bromid, $AgBr_2$ (bromyrite).
Iodid, AgI (iodyrite).
Fluorid, CaF_2 (fluorite).
Fluosilicate, K_2SiF_6 (hieratite).
Carbonate, $CaCO_3$ (calcite).
Meta-aluminate, $MgAl_2O_4$ (spinel).
Metaferrite, $FeFe_2O_4$ (magnetite).
Metachromite $FeCr_2O_4$ (chromite).
Metaniobate, $Fe(NbO_3)_2$ (columbite).
Metatantalate, $Fe(TaO_3)_2$ (tantalite).
Phosphate, $LiFePO_4$ (triphylite).
Arsenate, $FeAsO_4 \cdot H_2O$ (scorodite).
Vanadate, $BiVO_4$ (pucherite).
Antimonate, $Ca_2Sb_2O_7$ (atopite).
Nitrate, $NaNO_3$ (nitratine).
Borate, $AlBO_3$ (jeremejevite).
Sulfate, $BaSO_4$ (barite).
Chromate, $PbCrO_4$ (crocoite).
Selenite, $CuSeO_3 \cdot 2H_2O$ (chalcomenite).
Tellurite, $Fe(TeO_3)_3 \cdot 4H_2O$ (durdenite).
Tungstate, $CaWO_4$ (scheelite).
Molybdate, $PbMoO_4$ (wulfenite).
Metatitanate, $CaTiO_3$ (perovskite).
Orthosilicate $(Mg,Fe)_2SiO_4$(olivine).
Metasilicate, $CaSiO_3$ (wollastonite).
Trisilicate, $KAlSi_3O_8$ (orthoclase).
Dimetasilicate, $LiAl(Si_2O_5)_2$ (petalite).
Diorthosilicate, $Pb_3Si_2O_7$ (barysilite).

All the above are **normal salts**; that is, all the hydrogen of the acid or hydroxyl of the base has been replaced by metals or by acid radicals respectively. A compound in which only part of the hydrogen of the acid has been replaced by a metal is called an **acid salt.** Among minerals we have $KHSO_4$, and H_2CuSiO_4, which are called acid potassium sulfate, and acid copper silicate respectively. A compound in which only part of the hydroxyl of the base is replaced by an acid radical is called a **basic salt.** Among minerals we have $Cu_2(OH)_2CO_3$, $Cu_4(OH)_6Cl_2$, $Cu_2(OH)AsO_4$, and many others. These three compounds are called basic copper carbonate, chlorid, and arsenate respectively.

The formulæ of some minerals are written as though they consist of two or more separate molecules. These are called **molecular**

compounds for want of a better name. Among molecular compounds are double salts and hydrates or hydrous salts. **Double salts** are (1) salts composed of two metals with a common acid radical (example, dolomite $CaCO_3 \cdot MgCO_3$), (2) salts of a single metal with two distinct acid radicals (example, arsenopyrite $FeS_2 \cdot FeAs_2$), or (3) salts in which both the metal and acid radical are different (example, kainite $MgSO_4 \cdot KCl \cdot 3H_2O$).

Acid and basic salts may also be written in the form of double salts. $KHSO_4 = K_2SO_4 \cdot H_2SO_4$, $Cu_2(OH)_2CO_3 = CuCO_3 \cdot Cu(OH)_2$. Another kind of compound is Sb_2S_2O, antimony oxy-sulfid, which may be written $2Sb_2S_3 \cdot Sb_2O_3 (3Sb_2S_2O)$. Similarly Pb_2OCl_2 (or $PbCl_2 \cdot PbO$) is lead oxy-chlorid and $Pb_2Cl_2CO_3$ (or $PbCl_2 \cdot PbCO_3$) is lead chloro-carbonate.

Acid and basic salts when heated in the closed tube at a relatively high temperature (usually above 200° C.) give off water and this water is called **water of constitution.**

In other compounds water is more loosely held, and when heated is driven off at a temperature varying from about 100° C. to 200° C. This is the so-called **water of crystallization,** but this term is a misnomer, as water is not necessary for crystallization. Most anhydrous minerals occur in well formed crystals. Salts which give off a definite amount of water at low temperatures are called **hydrates** or **hydrous salts.** The formula is written as if they contain water as such. Examples: hydrous calcium sulfate, $CaSO_4 \cdot 2H_2O$ (gypsum); hydrous sodium borate, $Na_2B_4O_7 \cdot 10H_2O$ (borax). There may be various hydrates, for example, $MgSO_4 \cdot H_2O$ (kieserite); $MgSO_4 \cdot 6H_2O$ (hexahydrite), and $MgSO_4 \cdot 7H_2O$ (epsomite).

The following are examples of complicated salts which occur as minerals: $HNa_3(CO_3)_2 \cdot 2H_2O$, hydrous acid sodium carbonate (trona); $Fe_4(OH)_2(SO_4)_5 \cdot 17H_2O$, hydrous basic ferric sulfate (copiapite).

3. DERIVATION OF CHEMICAL FORMULÆ

Most minerals have a fairly definite chemical composition and hence may be represented by a formula. The formula is obtained

by dividing the percentage composition of the various elements or radicals by the corresponding combining weights as found in a table of atomic weights (pages 6–7). The ratio of these expressed in the simplest whole numbers possible gives the empirical formula. Example: An analysis of chalcopyrite from Phoenixville, Pennsylvania, furnished J. Lawrence Smith the results of column I.

	I	II	III	IV
Cu	32.85	÷ 63.6	=0.516	34.57
Fe	29.93	÷ 55.8	=0.536	30.54
S	36.10	÷ 32.1	=1.121	34.89
Pb	0.35			

Dividing by the combining weights given in the second column we have the figures of the third column, lead being omitted. These numbers are nearly in the ratio 1 : 1 : 2, hence the formula $CuFeS_2$. The theoretical percentages for chalcopyrite are given in the fourth column.

Discrepancies in analyses may be explained in a number of ways. It is very common for similar metals or acid radicals to replace each other in varying proportions. In this case the combining ratios of replacing metals or acid radicals are added together. An analysis of brown sphalerite from Roxbury, Connecticut, gave Caldwell the percentage composition of column I. Dividing by the atomic weights of column II we have the combining ratios of III. The sum of the combining ratios for Zn and Fe (1.033) is to the combining ratio for S (1.039) practically as 1 : 1. Hence the formula is (Zn,Fe)S, which means that iron replaces zinc in varying amounts. Analyses of sphalerite show an iron content varying from *nil* up to 18 per cent.

	I	II	III	IV
Zn	63.36	÷ 65.4	= 0.969	1.033
Fe	3.60	÷ 55.8	= 0.063	
S	33.36	÷ 32.1	= 1.039	1.039

Analyses of oxids, haloids, sulfids, and sulfo-salts are given as

percentages of the elements. This cannot be done with the oxygen salts as there is no way of determining oxygen directly; therefore the percentage composition of the oxygen salts must be expressed either as oxids, or as metals and acid radicals. At present it is customary to use the oxids. This is in accordance with the electro-chemical theory of Berzelius in which dualistic formulæ were used. Thus $FeSO_4$ was considered as $FeO{\cdot}SO_3$, FeO being the base or electropositive radical and SO_3, the acid or electronegative radical. Although these views are considered antiquated by modern chemists, still the custom is to employ the basic and acid anhydrids in stating the results of analysis. Thus $CaSO_4$ is given as CaO and SO_3. The method of giving the metals and acid radical is preferable if haloids or sulfids are present. In the ordinary method there is an excess of oxygen equivalent to the amount of halogen or sulfur present which must be deducted. For example, apatite is $Ca_5F(PO_4)_3$. The calculated percentage compositions are: CaO = 55.5, P_2O_5 = 42.3, F = 3.8; total = 101.6. The excess over 100 per cent is due to the fact that only part of the calcium is combined with the oxygen, as can be seen by expressing the formula in another way: $9CaO{\cdot}3P_2O_5{\cdot}CaF_2$. The oxygen equivalent of F is $\frac{1}{2}O$ with atomic weight of 8. The percentage compositions given above have been figured on the basis of a formula weight of 512.5 (504.5+8). [512.5 : 504.5 : : 101.6 : 100]. A much better way is to express the percentage compositions thus: Ca = 39.7, F = 3.8, PO_4 = 56.5; total = 100.0.

In the case of hydrous, acid, or basic salts of any kind, the water percentage is given, as the determination of water is often a practical means of identifying a mineral.

4. VARIATIONS IN THE CHEMICAL COMPOSITION OF MINERALS

In the foregoing discussion it was assumed that minerals have a definite chemical composition. Strictly speaking, this is true of only a comparatively few minerals such as some specimens

of quartz, calcite, and a few others. While other minerals approach definiteness of chemical composition many others are far from being definite.

In the first place, it should be emphasized that much of the variation from the theoretical values of chemical formulæ is due to mechanical impurities. Many apparently homogeneous substances prove on microscopic examination to be mixtures of two or more substances. For example, wollastonite ($CaSiO_3$) usually seems to effervesce in acids but the effervescence is due to admixed calcite. So-called cupriferous pyrite contains small amounts of chalcopyrite, as may be proved by examining polished surfaces of specimens with the reflecting or metallographic microscope. But complexity in chemical composition is not always proof of mechanical mixtures.

In homogeneous minerals the departure from fixed chemical composition can be explained in two or three different ways: (1) by solid solution of which isomorphism is a special case, and (2) by the fact that the mineral is of colloidal origin.

5. ISOMORPHISM

Many compounds of similar chemical composition, especially salts with the same acid radicals and related metals, have almost identical crystal forms. Such compounds are said to be **isomorphous.** Isomorphous substances have similar form, but except in the isometric system this does not mean that the form is identical. For example, the angle $(110 : 1\bar{1}0)$ for barite, $BaSO_4$, is 78° 22½′, while for celestite, $SrSO_4$, the corresponding angle is 75° 50′, and for anglesite, $PbSO_4$, it is 76° 16½′. Barite, celestite, and anglesite thus form an isomorphous group. Among prominent isomorphous groups of minerals are the following:

Pyrite	FeS_2
Smaltite	$(Co,Ni)As_2$
Cobaltite	$CoAsS$
Gersdorffite	$NiAsS$

	Marcasite	FeS_2
	Arsenopyrite	FeAsS
	Löllingite	$FeAs_2$
	Glaucodot	(Co,Fe)AsS
	Safflorite	$CoAs_2$
	Rammelsbergite	$NiAs_2$
	Tetrahedrite	$Cu_3SbS_3 + x(Fe,Zn)_6Sb_2S_9$
	Tennantite	$Cu_3AsS_3 + x(Fe,Zn)_6As_2S_9$
Ruby Silvers	Proustite	Ag_3AsS_3
	Pyrargyrite	Ag_3SbS_3
	Corundum	Al_2O_3
	Hematite	Fe_2O_3
	Cassiterite	SnO_2
	Rutile	TiO_2
	Diaspore	$Al(OH)_3 \cdot Al_2O_3$
	Goethite	$Fe(OH)_3 \cdot Fe_2O_3$
	Manganite	$Mn(OH)_3 \cdot Mn_2O_3$
	Calcite	$CaCO_3$
	Magnesite	$MgCO_3$
	Siderite	$FeCO_3$
	Rhochrosite	$MnCO_3$
	Smithsonite	$ZnCO_3$
	Aragonite	$CaCO_3$
	Strontianite	$SrCO_3$
	Witherite	$BaCO_3$
	Cerussite	$PbCO_3$
	Fluor-apatite	$Ca_{10}F_2(PO_4)_6$
	Chlor-apatite	$Ca_{10}Cl_2(PO_4)_6$
	Dahllite	$Ca_{10}(CO_3)(PO_4)_6$
	Voelckerite	$Ca_{10}O(PO_4)_6$
	Svabite	$Ca_{10}F_2(AsO_4)_6$
	Pyromorphite	$Pb_{10}Cl_2(PO_4)_6$
	Mimetite	$Pb_{10}Cl_2(AsO_4)_6$
	Vanadinite	$Pb_{10}Cl_2(VO_4)_6$
	Barite	$BaSO_4$
	Celestite	$SrSO_4$
	Anglesite	$PbSO_4$
	Alunite	$KAl_3(OH)_6SO_4$
	Jarosite	$KFe_3(OH)_6SO_4$

	Ilmenite	$FeTiO_3$
	Geikielite	$MgTiO_3$
	Pyrophanite	$MnTiO_3$
	Senaite	$(Fe,Mn,Pb)TiO_3$
Garnet	Grossularite	$Ca_3Al_2(SiO_4)_3$
	Pyrope	$Mg_3Al_2(SiO_4)_3$
	Almandite	$Fe_3Al_2(SiO_4)_3$
	Spessartite	$Mn_3Al_2(SiO_4)_3$
	Andradite	$Ca_3Fe_2(SiO_4)_3$
	Uvarovite	$Ca_3Cr_2(SiO_4)_3$

Many isomorphous compounds are capable of crystallizing together in various proportions and thus form what are known as **isomorphous mixtures.** There are many such cases among minerals which fact is very useful in interpreting mineral analyses. Chromite is an isomorphous mixture of $FeCr_2O_4$, $FeFe_2O_4$, $MgCr_2O_4$, $MgAl_2O_4$, and $FeAl_2O_4$, all of which are known as minerals. The formula used to express the chemical composition is as follows: (Fe″, Mg) (Cr, Al, Fe‴)$_2O_4$, which means that the combined proportion of chromium, aluminum, and ferric iron is twice (molecularly) that of ferrous iron and magnesium together. Among prominent isomorphous mixtures are: sphalerite (Zn,Fe)S, smaltite $(Co,Ni)As_2$, columbite $(Fe,Mn)(Nb,Ta)_2O_6$, campylite $Pb_5Cl(As,P)_3O_{12}$, endlichite $Pb_5Cl(As,V)_3O_{12}$, pisanite $(Fe,Cu)SO_4 \cdot 7H_2O$, wolframite $(Fe,Mn)WO_4$, actinolite $Ca(Mg,Fe)_3(SiO_3)_4$, and epidote $Ca_2(Al,Fe)_3(OH)(SiO_4)_3$. The garnets are isomorphous mixtures of the compounds mentioned above. It is rare to find an analysis of garnet that will correspond exactly to any one of these formulæ.

The physical properties of isomorphous mixtures vary continuously; for this reason the term **solid solution** is sometimes used. The best test of isomorphism is the ability to form mixed crystals.

6. SOLID SOLUTIONS NOT DUE TO ISOMORPHOUS MIXTURES

While most of the variations in the chemical composition of crystalline minerals may be explained by isomorphism there are

some cases which cannot be so explained. For example, pyrrhotite contains a slight excess of sulfur over that required for the formula FeS. Formerly this was expressed by the formula Fe_nS_{n+1}, in which n varies from 5 to 15, in accordance with the law of multiple proportions and the belief that every mineral has a definite composition. This we know to be false and the modern way of expressing the chemical composition of pyrrhotite is by means of the following formula: $FeS(S)_x$, which signifies that pyrrhotite is regarded as a solid solution of sulfur in ferrous sulfid.

Another example of solid solution is nepheline, which contains an excess of silica over that required for the formula $(Na,K)AlSiO_4$.

The color of many minerals is due to a solid solution of some pigment (either organic or inorganic) in the mineral.

7. MINERALS OF COLLOIDAL ORIGIN

Most of the amorphous minerals, such as opal, cliachite, and collophane, are of colloidal origin. They are apparently due to the gradual hardening or setting of a gelatinous mass. Such hardened **gels** were called *porodine* by Breithaupt. The mechanism of the hardening of a gel is not well understood nor is the nature of the gel itself, but some of the hardened gels are common minerals and so deserve our attention.

When a substance is precipitated in the form of minute particles intermediate in size between ordinary visible suspensions and solutions, it possesses peculiar properties due to the enormous surface exposed. The phenomenon of surface tension plays an important part in determining these properties. Such a state or condition of a substance is called the **colloidal** or **dispersed state.** Colloidal substances, or more accurately speaking substances in the colloidal condition, on account of the great surfaces exposed, have a tendency to take up or adsorb other substances from the solutions in which they are formed. This adsorption seems to be, to a large extent, selective, and for this

reason most of the amorphous minerals of colloidal origin approach in chemical composition that of the corresponding crystalline mineral. This was first emphasized by the Austrian mineralogist, Cornu, in 1909. Collophane, for example, is very much like crystalline dahllite, $3Ca_3(PO_4)_2 \cdot CaCO_3$, in chemical composition. Nearly all the well-established amorphous minerals have crystalline equivalents. Opal is the amorphous equivalent of chalcedony and quartz. Cliachite is the amorphous equivalent of gibbsite [$Al(OH)_3$]. Turyite is probably the amorphous equivalent of hematite. Psilomelane is the amorphous equivalent of hollandite or romanchéite. Pitchblende is probably the amorphous equivalent of uraninite. Halloysite is the amorphous equivalent of kaolinite. Cornuite, recently described by the author, is the amorphous equivalent of chrysocolla. Some common minerals such as calcite, barite, fluorite, etc., have no amorphous equivalents, or at least they have not yet been described.

Because of adsorption the amorphous minerals vary somewhat in chemical composition but there is also variation in the water content. Practically all the amorphous minerals contain water, the reason being that they are hardened hydrogels, that is, gels formed in water solution. While the water is adsorbed when the colloid is first formed, there is a probability of solid solution being formed by the diffusion of the water and also of the other adsorbed substances. The water, however, is variable in amount and so may be represented by: $(H_2O)_x$. Although practically always present, the water is probably not essential.

8. POLYMORPHISM

Something besides chemical composition must be taken in account in the study of minerals, for it is a well-known fact that many chemical substances exist in two or more distinct forms. That is, they occur in crystals with different internal arrangements of atoms, usually belong to different crystal systems, and have dissimilar physical properties.

Such compounds are called **polymorphs.** A familiar example is carbon which occurs as graphite in soft, opaque, hexagonal crystals, and as diamond in very hard, transparent, isometric crystals. Polymorphous elements like carbon are called allotropic. Among polymorphous minerals may be mentioned the following:

C	Diamond—Isometric Graphite—Hexagonal
FeS_2	Pyrite—Isometric Marcasite—Orthorhombic
$CaCO_3$	Calcite—Hexagonal Aragonite—Orthorhombic
$KAlSi_3O_8$	Orthoclase—Monoclinic Adularia—Monoclinic Microcline—Triclinic
SiO_2	α-Quartz—Hexagonal ($A_3.3A_2$) β-Quartz—Hexagonal ($A_6.6A_2$) Chalcedony—(?) Tridymite—Hexagonal (Symmetry unknown) Cristobalite—Isometric
TiO_2	Rutile—Tetragonal ($\dot{c} = 0.64$) Octahedrite—Tetragonal ($\dot{c} = 1.77$) Brookite—Orthorhombic
$Ca_2Al_3(OH)(SiO_4)_3$	Zoisite—Orthorhombic Clinozoisite—Monoclinic
Al_2SiO_5	Kyanite—Triclinic Andalusite—Orthorhombic ($\breve{a} = 0.986$, $\dot{c} = 0.702$) Sillimanite—Orthorhombic ($\breve{a} = 0.970$, $\dot{c} = ?$
$H_2Mg_3Si_2O_9$	Antigorite—Orthorhombic Chrysotile—Orthorhombic

Polymorphism seems to be a general phenomenon of nature.

Numerous examples of polymorphism occur in prepared compounds. Sulfur may be prepared in at least four modifications: α-sulfur (orthorhombic); β-sulfur, (monoclinic); γ-sulfur, (also monoclinic, but with different axial ratio from β-sulfur); δ-sulfur,

(rhombohedral). Mercuric iodid, HgI_2, exists in a red tetragonal modification (from solutions), and also in a yellow orthorhombic modification (from fusion or sublimation).

In most cases it is the temperature which determines the modification formed. Thus calcite forms from aqueous solutions below 30° C., while aragonite forms above 30° C. For example, the crust of $CaCO_3$ often formed in a tea-kettle is aragonite.

The silica minerals furnish the best known example of polymorphism. A discussion of the stability relations of these minerals will be found on page 265.

B. BLOWPIPE ANALYSIS

The advantage of blowpipe analysis lies in the fact that the tests are simple, the apparatus portable, and the reagents few in number. By means of the blowpipe an intense heat (about 1500° C.) can be obtained on a small scale, and a variety of chemical effects can be brought about. At the same time it is the author's opinion that, with a few exceptions, blowpipe analysis is of value only in the determination of minerals.

Blowpipe analysis will be discussed under four headings: (1) apparatus, (2) reagents, (3) operations, and (4) select tests. Section 3 may be used in preliminary tests and also as determinative tables, while tests for the metals and acid radicals may be found in section 4 arranged alphabetically by elements.

1. APPARATUS USED IN BLOWPIPE ANALYSIS

Blowpipe. The blowpipe is made in a variety of forms. The simplest blowpipe is a brass tube about 10 inches long, bent at one end. A bulb is sometimes added to condense moisture. A more elaborate form is a nickel-plated tube with a moisture chamber at one end and a smaller tube at right angles which is provided with either a brass or a platinum tip.

Where gas is available, the gas blowpipe is undoubtedly the most convenient form on account of the perfect control of the

flame. The gas blowpipe is similar to the nickel-plated form just described, but the smaller right-angled tube is a double one; the inner one for air, the outer one for gas.

Fuel. Gas is the most convenient and commonly used fuel. If a Bunsen burner is used, it is well to use a small tube which fits the top of the Bunsen burner and is provided with a flange in which the tip of the blowpipe rests. The luminous flame of the Bunsen burner should be used with the blowpipe.

Where gas is not available, alcohol, lard oil, or olive oil may be burned in a lamp provided with a wick. Candles are even more convenient. For field use a good combination is alcohol for heating, and candles for use with the blowpipe.

Charcoal. Slabs of charcoal about 4 inches long, 1 inch wide, and ¾ inch thick, are used as a blowpipe support. They may be purchased from dealers in chemical apparatus.

Plaster. A paste of plaster-of-Paris with water is poured out on oiled glass in sheets about ¼ inch thick. Before hardening, it is marked off in rectangles about 4 inches long and 1 inch wide.

Platinum Tipped Forceps. These forceps are essential for testing the fusibility of minerals, and are useful for other purposes. Arsenic, antimony, lead, and copper minerals should be fused on charcoal, for these metals alloy with platinum.

Hammer. A small square-faced hammer of about one-fourth pound weight is indispensable.

Anvil. A small block of steel, square or rectangular in cross-section, and about ½ inch thick, is convenient for powdering minerals and has many other uses.

Platinum Wire. No. 27 platinum wire is the best size for general use. The wire may be fused into a piece of glass tubing, or held in a special holder made for the purpose.

Test Tubes. The most convenient size is 4 inches long and ½ inch in diameter.

Glass Tubing. Soft glass tubing of 7 mm. outside diameter is best for most purposes, but it is well to have a variety of sizes. For some tests hard glass tubing is preferable.

Watch Glasses. These are needed especially for solubility tests. The best size is 2 inches in diameter.

Magnet. A magnetized knife-blade answers the same purpose and is more convenient.

Lens. A Coddington or aplanatic triplet of ¾-inch focus is recommended. This gives a magnification of about 15 diameters.

A triangular file, blue glass (or Merwin's flame color screen), **funnels,** and **filter-paper** are also essential.

The following pieces of apparatus are not essential, but will be found very useful.

Diamond Mortar. A mortar made of a piece of cylindrical tool-steel about 1 inch long and about 1 inch in diameter, with a convenient size cylindrical cavity and pestle to fit, is very convenient for reducing a mineral to a coarse powder.

Agate Mortar. A small agate mortar, 1½ inches in diameter, is used for fine grinding of minerals.

Steel Pliers are used for breaking off fragments of minerals.

Platinum Foil. A thin sheet of platinum about ½ by ¾ inch may be used for sodium carbonate fusions.

Dropping Bulbs are useful for reagents that are needed in small amounts, such as cobalt nitrate solution.

Small beakers, porcelain crucibles, wash-bottles, etc., may often be used to advantage.

2. REAGENTS USED IN BLOWPIPE ANALYSIS

A. Dry Reagents

Dry reagents should be kept in wide-mouthed glass bottles. It is convenient to have a set of four to six of these bottles in a wooden stand.

Sodium Carbonate, Na_2CO_3. Baking "soda" ($NaHCO_3$) may be used instead. Sodium carbonate is used principally for fusions.

Borax, $Na_2B_4O_7{\cdot}10H_2O$, is used principally for bead tests. The ordinary commercial salt may be used. Borax glass is simply fused borax, used in silver cupellation.

Sodium Metaphosphate, $NaPO_3$. This is used for the bead tests, in which salt of phosphorus, $HNaNH_4PO_4 \cdot 4H_2O$, is usually employed. It can be made by fusing salt of phosphorus, and is much more convenient, as a salt of phosphorus bead usually drops off the loop of platinum wire when heated.

Potassium Acid Sulfate, $KHSO_4$. This is used in bismuth flux, in boric acid flux, and also independently.

Iodid Flux is made by grinding together 1 part KI, 1 part $KHSO_4$, and 2 parts S. It is used principally on plaster tablets, but also on charcoal.

Boric Acid Flux is a mixture of 1 part of finely powdered fluorite (CaF_2) with 3 parts of $KHSO_4$.

Cupric Oxid, CuO. Powdered malachite may be used instead.

Tin. Ordinary tin-foil (sheet lead with a thin coating of tin) is used as a reducing agent.

Zinc. Zinc in the form of shavings or sheets is used in testing cassiterite.

Test Lead. Lead in a granulated form such as is used in assaying.

Bone-Ash, such as is used in assaying, is moulded into cupels on charcoal. Prepared cupels, 1 inch in diameter, may be used.

B. Wet Reagents

The following are the more important wet reagents used in the determination of minerals, though occasionally any of the reagents of the chemical laboratory may be found useful.

Hydrochloric Acid, HCl. Two parts concentrated acid (sp. gr. 1.20) with 3 parts distilled water is the acid used for general purposes. (5N.)[1]

Nitric Acid, HNO_3. One part concentrated acid (sp. gr. 1.42) with 2 parts water. (5N.)

Sulfuric Acid, H_2SO_4. One part concentrated acid (sp. gr. 1.84) with 4 parts of water (5N). It should be diluted with great care by pouring acid into the water rather than the reverse.

Citric Acid. As this is a solid it may be used in the field for testing carbonates. A water solution is used.

[1] N means a normal solution, *i.e.*, one that contains one gram-equivalent of the substance in one liter (a gram atom of hydrogen is the unit).

Aqua Regia is a mixture of 3 parts of conc. HCl and 1 part of conc. HNO_3. It is made up when needed.

Ammonium Hydroxid, NH_4OH. One part of concentrated NH_4OH (sp. gr. 0.96) to 4 parts of solution.

Ammonium Oxalate, $(NH_4)_2CO_4 \cdot 2H_2O$. 40 grams of salt to a liter of solution. ($\frac{1}{2}$N.)

Sodium Acid Phosphate, $Na_2HPO_4 \cdot 12H_2O$. 60 grams to a liter of solution. ($\frac{1}{2}$N).

Ammonium Molybdate, $(NH_4)_2MoO_4$. This reagent, which is difficult to prepare, may be made by dissolving 100 grams of MoO_3 in 250 ccm. NH_4OH (sp. gr. 0.96) with 250 ccm. of water. After cooling, this solution is poured into 750 ccm. HNO_3 (sp. gr. 1.2) with 750 ccm. water while stirring.

It may also be prepared by dissolving 150 g. of $(NH_4)_2MoO_4$ crystals in a liter of distilled water to which a liter of HNO_3 (sp. gr. 1.1) has been added.

Silver Nitrate, $AgNO_3$. 43 grams of the salt to a liter of solution. ($\frac{1}{2}$N.) It should be kept in an opaque bottle.

Barium Chlorid, $BaCl_2 \cdot 2H_2O$. 61 grams of salt to a liter of solution. ($\frac{1}{2}$N.)

Cobalt Nitrate, $Co(NO_3)_2 6H_2O$. 73 grams of the salt to a liter of solution. ($\frac{1}{2}$N.)

Alcohol. 95 per cent. ethyl alcohol.

C. Additional Reagents used in Qualitative Analysis

Acetic Acid, $HC_2H_3O_2$. 30 per cent. acid. (5N.)

Ammonium Carbonate, $(NH_4)_2CO_3$. 192 grams to a liter of solution, including 100 ccm. of NH_4OH. (4N).

Ammonium Chlorid, NH_4Cl. 267 grams to a liter of solution. (5N). (The solid reagent is also used for alkali fusions with $CaCO_3$.)

Ammonium Sulfid, $(NH_4)_2S$. Saturate conc. NH_4OH with H_2S, and add an equal volume of NH_4OH. Dilute with three volumes of water. (4N.)

Ammonium Sulfid, Yellow, $(NH_4)_2S_x$. This is made by adding flowers of sulfur to $(NH_4)_2S$.

Barium Hydroxid, $Ba(OH)_2 \cdot 8H_2O$. Used for the detection of carbon dioxide.

Calcium Carbonate, $CaCO_3$. The solid reagent.

Chloroplatinic Acid, H_2PtCl_6. This is made by dissolving thoroughly cleaned scrap platinum in aqua regia.

Ether-Alcohol. Equal volumes of ether and absolute alcohol.

Dimethylglyoxime. A one per cent. solution of the reagent in alcohol.

Ferrous Sulfate, $FeSO_4 \cdot 7H_2O$. Concentrated solution.

Lead Acetate, Pb $(C_2H_3O_2 \cdot 3H_2O.)$ 95 grams to a liter of solution. ($\frac{1}{2}$N.)

Potassium Chromate, K_2CrO_4. 49 grams to a liter of solution. (½N.)
Potassium Cyanid, KCN. 33 grams to a liter of solution. (½N.)
Potassium Ferricyanid, $K_3Fe(CN)_6$. 55 grams to a liter of solution. (½N.)
Potassium Ferrocyanid, $K_4Fe(CN)_6 \cdot 3H_2O$. 53 grams to a liter of solution. (½N.)
Potassium Hydroxid, KOH. Solid reagent.
Sodium Acetate, $NaC_2H_3O_2$. The solid dissolved in ten parts of water.
Sodium Carbonate, Na_2CO_3. Solid reagent.
Sodium Cobaltic Nitrite, $Na_3Co(NO_2)_6$. This is made by adding 1 part of $Co(NO_3)_2$ solution to 3 parts of acetic acid and 5 parts of a 10 per cent. solution of $NaNO_2$.
Sodium Hydroxid, NaOH. Solid reagent.
Sodium Nitrate, $NaNO_3$. Solid reagent.
Stannous Chlorid, $SnCl_2 \cdot 2H_2O$. 56 grams to a liter of solution. (½N.)
Tartaric Acid, $C_4H_4O_2$. Solid reagent.

3. THE OPERATIONS OF BLOWPIPE ANALYSIS

The list of tests given here serves both as an outline to follow with known substances, and also as determinative tables for unknown minerals. As only the more important tests are included decided results must be obtained to be of value.

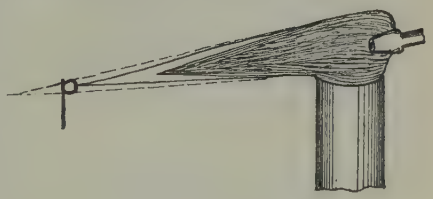


Fig. 1.—Oxidizing flame.

I. Use of the Blowpipe.

To produce a steady flame, maintain a reservoir of air by keeping the cheeks slightly distended, and by breathing through the nose.

Oxidizing Flame (O.F.). The extreme outer tip (Fig. 1) of a *small* flame produced by a rather *strong* blast of air is most favorable for oxidation. If a candle, lamp, or Bunsen burner is used, the tip of the blowpipe is held just *within* the flame. One's ability to produce a good oxidizing flame may be judged by fusing borax on a ⅛ inch loop of platinum wire and then adding a little MoO_3. The bead should become colorless.

Reducing Flame (R.F.). The tip of the inner luminous cone (Fig. 2) of a *large* flame produced by a *gentle* blast of air is most favorable for reduction. If a candle, lamp, or Bunsen burner is used, the blowpipe tip is held just *outside* the flame and the whole flame is directed toward the assay. A borax bead made amethyst colored with a little MnO_2 in O.F. should become colorless when heated in a good reducing flame. The reducing flame should be luminous, but just hot enough to prevent the deposition of soot.

II. Flame Tests.

In the high temperature of the blowpipe flame, many compounds are volatilized; and the colors produced are often characteristic. They should be viewed against a dark background, such as a piece of charcoal. The chlorids, as a rule, are the most volatile compounds of the metals, so HCl should be used, but in some cases H_2SO_4 is better. Platinum wire is used except for compounds of As, Sb, Pb, and Cu, which should be heated on charcoal. The wire should be cleaned with HCl after each test, but it should never be placed in a reagent bottle on account of the danger of contaminating the reagent.

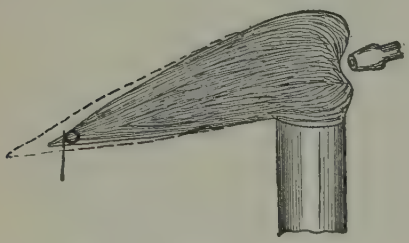


Fig. 2.—Reducing flame.

Red Flames.

Purplish red—**lithium** compounds.
Crimson—**strontium** compounds.
Orange red—**calcium** compounds.

Yellow Flames.

Intense yellow (masked by blue glass or flame-color screen)—**sodium** compounds.

Green Flames.

Yellowish green—**barium** compounds.
Yellowish green—**molybdenum** compounds.
Emerald green—**copper** compounds (without HCl).
Bright green (use H_2SO_4)—**boron** compounds.
Pale bluish green (use H_2SO_4)—**phosphates.**
Pale bluish green—**tellurium** compounds.
Pale bluish green—**antimony** compounds.
Bluish green—**zinc** compounds.

Blue Flames.

Azure blue—**copper** compounds (with HCl).
Pale blue—**arsenic** compounds.
Pale blue—**lead** compounds.

Violet Flames.

Pale reddish violet (use blue glass or flame-color screen) —**potassium** compounds. (Some potassium compounds such as orthoclase must be fused with Na_2CO_3, to obtain the flame test.)

The spectroscope must be used to detect such elements as rubidium, calcium, thallium, indium, etc., and also to detect very small amounts of the above mentioned elements.

III. Open Tube Tests.

Glass tubes about 4 or 5 inches long and open at *both* ends are used. The substance, which may be introduced into the tube by means of a folded trough of paper, is placed about 1 inch from one end of the tube. The tube is heated gently in a horizontal position at first and then is gradually inclined while still heating; thus a current of air is produced. If heated too rapidly or too near the end of the tube a closed tube effect is the result.

Odor of burning matches (SO_2)—**sulfids** and **sulfo-salts.**

Sublimate of minute brilliant crystals (As_2O_3)—**arsenids** and **sulfarsenites.**

Non-volatile amorphous sublimate (Sb_2O_4) on under side of tube—**antimony sulfid** and **sulfantimonites.**

Gray metallic globules (Hg)—**mercury sulfid.**

IV. Closed Tube Tests.

Glass tubes closed at *one* end are used. Two closed tubes may be made at the same time by fusing a piece of tubing 5 or 6 inches long at its middle point and pulling it apart when hot. Tubes should be clean and dry before they are used.

1. Change in Appearance.

Decrepitates (flies to pieces)—characteristic of many minerals.

Turns black—**copper** minerals and numerals containing organic matter.

Turns dark red—**iron** minerals.

Turns yellow—**lead** minerals.

Turns yellow (white on cooling)—**zinc** minerals.

2. Formation of Sublimates.

Yellow sublimate (S)—some **sulfids.**

Black metallic mirror (As)—**arsenids.**

Reddish yellow (AsS)—**arsenic sulfids** and **sulfarsenites.**

Reddish brown (Sb_2S_2O)—**antimony sulfids** and **sulfantimonites.**

White volatile sublimate—**ammonium salts.**

Water (H_2O)—**hydroxids, hydrous, basic,** and **acid salts.**

3. Formation of Gases.

Colorless and odorless (CO_2)—**carbonates** (detected by $Ba(OH)_2$.

Colorless and odorless (O)—**manganese dioxids** (detected by glowing charcoal).

Brownish-red and pungent odor (NO_2)—**nitrates.**

V. Treatment on Charcoal.

The substance, either alone or intimately mixed with some reagent, is heated in a shallow circular cavity at one end of the charcoal, which is made by revolving a coin or end of a knife handle. O.F. or R.F. is used according to the desired effect.

1. Evolution of Gas.

Odor of burning matches (SO_2)—**sulfids** and **sulfo-salts** (use O.F.).

Arsin odor (AsH_3)—**arsenids** and **sulfarsenites** (use R.F.).

2. Formation of Sublimates. (Use O.F.).

It is well to run a blank test to observe ash of the charcoal.

White sublimate near assay (Sb_2O_3)—**antimony** compounds.

White sublimate far from assay (As_2O_3)—**arsenic** compounds.

White sublimate, yellow when hot (ZnO)—**zinc** compounds.

White sublimate, yellow near assay ($PbSO_4$)—**lead sulfid.**

Yellow sublimate (PbO)—**lead** compounds.

Yellow sublimate (Bi_2O_3)—**bismuth** compounds.

3. Reduction with Sodium Carbonate.

Mix intimately 1 part of the finely powdered substance with 3 parts of Na_2CO_3 and fuse in R.F. on charcoal.

Magnetic particles (Fe_3O_4,Ni,Co)—**iron, nickel,** and **cobalt** compounds.

Metallic button, gray and malleable (Pb)—**lead** compounds.

Metallic button, somewhat malleable but brittle on edges (Bi)—**bismuth** compounds.

Metallic button, malleable white (Ag)—**silver** compounds.

Metallic button, malleable yellow (An)—**gold** compounds.

Metallic button, malleable red (Cu)—**copper** compounds.

Metallic button, malleable white (Sn)—**tin** compounds.

4. Fusion Test for Sulfur.

An intimate mixture of a finely powdered sulfid or sulfo-salt with about three parts of sodium carbonate is heated in O.F. on a thin sheet of mica placed on charcoal (or on platinum foil if absence of As, Sb, Pb, and Cu is assured). The fused mass placed on a bright silver coin with several drops of water and crushed will give a black stain (Ag_2S). The reactions are: $R''S + Na_2CO_3 = Na_2S + R''CO_3$. $Na_2S + 2Ag + H_2O + O = Ag_2S + 2NaOH$. Tellurids give the same test as sulfids.

It is well to run a blank test to see if the gas or sodium carbonate contains sulfur.

Sulfates also give this test if heated in a strong R.F. on charcoal instead of on mica. The addition of powdered charcoal helps the reaction.

As the sulfur compounds sink into the charcoal, the same spot cannot be used more than once.

5. Treatment with Cobalt Nitrate.

The substance is heated intensely on charcoal before and after adding a dilute solution of cobalt nitrate. In this way cobalt aluminate, cobalt zincate, etc., are formed.

Deep blue coloration—*infusible* **aluminum** compounds and **zinc silicates.** (Almost any fusible substance will give a blue color, for a cobalt glass is formed.)

Bright green coloration—**zinc** compounds, except the silicates which give a blue coloration.

Bluish-green coloration—**tin** compounds.

Pale pink coloration—**magnesium** compounds (not very satisfactory).

VI. Treatment on Plaster with Iodid Flux.

An intimate mixture of the substance with an equal quantity of iodid flux (2 parts S, 1 part KI, and 1 part $KHSO_4$) is heated gently at one end of a plaster tablet. In this way iodids of the metals are obtained.

Yellow sublimate (PbI_2)—**lead** compounds.

Orange sublimate stippled with peach-red (SbI_3)—**antimony** compounds.

Purplish-chocolate sublimate (BiI_3) with underlying scarlet —**bismuth** compounds.

Scarlet sublimate (dark greenish-yellow if overheated) (HgI_2)—**mercury** compounds.

VII. Treatment on Charcoal with Iodid Flux.

The same reagent as above, but with charcoal instead of plaster as a support.

Greenish-yellow sublimate (PbI_2)—**lead** compounds.

Scarlet sublimates (BiI_3)—**bismuth** compounds.

Faint yellow sublimate (HgI_2, etc.)—**mercury, arsenic,** and **antimony** compounds.

VIII. Borax Bead Tests.

Borax beads are made by fusing borax in a 3 mm. loop of platinum wire formed around the sharpened end of a lead pencil. Great care should be used in O.F. and R.F. Sulfids should be first roasted by gently heating the powdered substance spread out on charcoal. It is well to preserve the beads in a little frame or glass tube for future reference. The colors refer to cold beads, except when otherwise mentioned. Many elements giving colorless or pale yellow beads are not mentioned.

	Violet	Blue	Green	Red	Brown	Yellow	Colorless
Co.		O.F.,R.F.					
Cr			O.F.,R.F.				
Cu		O.F.	O.F.,R.F.	(saturated) R.F. (opaque)			
Fe			R.F.			O.F.	
Mn	O.F.						R.F.
Mo					R.F.		O.F.
Ni	O.F. (hot)				O.F. (cold)		R.F. (turbid gray)
Ti	R.F.						O.F.
U			R.F.			O.F.	
V			R.F.				O.F.
W						R.F.	O.F.

IX. Sodium Metaphosphate Bead Tests.

Beads of sodium metaphosphate, $NaPO_3$, are made in the same way as with borax. Salt of phosphorus or microcosmic salt, ($HNaNH_4PO_4 \cdot 4H_2O$) may also be used, for on heating it loses NH_3 and H_2O, and is converted into $NaPO_3$. The colors refer to cold beads.

	Violet	Blue	Green	Red	Yellow	Colorless
Co		O.F.,R.F.				
Cr			O.F.,R.F.			
Cu		O.F.		(saturated) R.F. (opaque)		
Fe					O.F. (pale)	O.F.,R.F.
Mn	O.F.					R.F.
Mo			R.F.			O.F.
Ni					O.F.,R.F.	
Ti	(saturated) R. F.					O.F.
U			O.F.,R.F.			
V			R.F.		O.F.	
W		R.F.				O.F.

Silica is insoluble in a $NaPO_3$ bead, but with silicates the beads dissolve (sometimes coloring the bead), while the silica usually remains as a translucent mass, often the shape of the original fragment, which floats around in the bead. A few other compounds, such as Al_2O_3 and TiO_2, are very slowly soluble in a $NaPO_3$ bead.

X. Reduction Color Tests.

Saturate several $NaPO_3$ beads with the finely ground substance, and heat on charcoal with metallic tin in R.F. Dissolve in dilute HCl, add tin, and then boil.

Violet solution—**titanium** compounds.

Deep blue solution—**tungsten** compounds.

Brown solution—**molybdenum** compounds.

Green solution—**chromium, uranium,** and **vanadium** compounds.

XI. Sodium Carbonate Bead Test.

Beads of sodium carbonate are made the same as borax and sodium metaphosphate. The O.F. is used. The beads are opaque and not clear as with borax.

Bluish-green opaque bead (Na_2MnO_4)—**manganese** compounds (a very delicate test).

Yellow opaque bead (Na_2CrO_4)—**chromium** compounds.

Effervescence—**silica.** $Na_2CO_3 + SiO_2 = Na_2SiO_3 + CO_2$. (The bead will be clear if equal molecular quantities are used.)

XII. Treatment with Acid Potassium Sulfate.

The substance is mixed with $KHSO_4$ and heated in a test-tube or closed tube.

Red-brown fumes with pungent odor (NO_2)—**nitrates.**

Colorless gas with HCl odor (HCl)—**chlorids.**

Colorless gas which etches glass (HF)—**fluorids.**

Colorless gas with disagreeable odor (H_2S)—**sulfids.**

Colorless, odorless gas (CO_2)—**carbonates.**

XIII. Fusibility Tests.

Long thin splinters of the mineral about 1 mm. in diameter held with platinum-tipped forceps or wrapped with a coil of platinum wire (in the absence of platinum forceps or wire a splinter may be stuck into a piece of charcoal) are heated in the hottest part of the flame, which is just beyond the tip of the inner

cone (see Fig. 3) of a small sharp O.F. flame (rather strong blast). Metallic substances should be heated on charcoal as they may contain As, Sb, or Pb which will alloy with the platinum. Powders or substances which fly to pieces when heated may be ground with a little water into a paste, which after careful drying can be heated in the forceps or on charcoal.

Scale of Fusibility

1. Fuses easily in luminous flame or in the closed tube—**stibnite.**

Fig. 3.—Position of assay in testing fusibility.

2. Fuses with difficulty in luminous flame or in the closed tube—**chalcopyrite.**
3. Fuses easily in blowpipe flame—**almandite (garnet).**
4. Fuses on edges easily in blowpipe flame—**actinolite.**
5. Fuses on edges with difficulty—**orthoclase.**
6. Fuses only on thinnest edges—**enstatite.**
7. Infusible, even on thinnest edges—**quartz.**

Not only the degree, but also the manner of fusion should be noted. The substance may fuse either to a clear, opaque, or colored glass; quietly, with intumescence (bubbling), or with exfoliation (spreading out like leaves of a book).

XIV. Blowpipe Silver Assay.

A qualitative test for silver in ores may easily be carried out by means of the blowpipe. The method is similar to that used in assaying except that it is on a smaller scale.

By using an assay centner (100 mg.) of ore and measuring the silver button obtained on an ivory scale made for the purpose, one may obtain quantitative results which, after some practice, are very satisfactory.

(1) Mix finely powdered ore intimately with one volume of

borax glass (made by fusing borax) and one volume of test lead. If ore contains galena it is not necessary to add test lead. (2) Fuse mixture in a deep cavity in charcoal with a strong R.F. for several minutes. The silver is collected by the lead button. (3) After cooling remove lead from charcoal and hammer off the slag. (4) Add fresh borax glass and heat in O.F. until the quantity of lead is considerably diminished. Again hammer off *every particle* of the slag. (5) Prepare a cupel by filling a large cavity in charcoal with *very slightly* moistened bone-ash and making a smooth concave depression with a mold (the end of a large test-tube will do). Heat cupel gently and remove all loose particles. (6) Carefully place the cube of lead (which should be not more than 2 or 3 mm. in diameter) on the cupel and fuse in O.F. by blowing across the top of it (use a small flame and strong blast and revolve the cupel occasionally). The oxidation produces a thin film of lead oxid showing interference colors, but when the lead is all absorbed, the film suddenly disappears or "blicks," and a minute sphere of silver, which may also contain gold, remains. The final oxidation of the lead must proceed without interruption, otherwise it may be necessary to repeat the entire operation from the beginning.

If the button shows a yellow tinge, gold is present. The silver may be removed by dissolving the button in nitric acid, but if much gold is present it is necessary to add some silver to the button in order to separate the gold from the silver.

XV. Solubility Tests.

In the absence of any special phenomena such as the evolution of a gas, or change in color, the only accurate way of testing solubility is to boil a small amount of the solvent with the substance for some time, and then to filter or decant the clear liquid and evaporate it to dryness. A residue indicates that the substance is soluble (anhydrite furnishes a good example of a soluble mineral which on hasty examination one might call insoluble). If in doubt as to the solubility run a blank test with an equal

quantity of solvent alone. A water solution of the residue gives a precipitate with a solution of sodium carbonate, except in the case of alkali compounds, but among minerals these are all readily soluble in water or contain other elements that are precipitated.

Soluble in water—**nitrates,** some **chlorids,** some **sulfates,** some **borates,** some **carbonates.**

Soluble in HCl—all **carbonates,** some **sulfids,** some **sulfates, borates,** some **phosphates,** some **silicates** (see p. 495), **iron oxids,** and **iron hydroxids.**

Soluble in HNO_3, but insoluble in HCl—most **sulfids** and **sulfosalts.**

Soluble in aqua regia—**gold** and **platinum.**

Soluble in HF—**silica** and nearly all the **silicates.**

Insoluble in acids but soluble in other liquids—**cerargyrite,** soluble in NH_4OH; **anglesite,** soluble in $NH_4(C_2H_3O_2)$; **sulfur,** soluble in CS_2.

Insoluble, but decomposed by fusion with Na_2CO_3—most **silicates, chromite, wolframite, barite,** and **celestite.** For method of treatment see note 4, for silicates, p. 49.

Insoluble, not completely decomposed by Na_2CO_3 fusion, but decomposed by fusion with KOH in a nickel crucible—**cassiterite, corundum,** and **rutile.**

Evolution of Gas.

Colorless, odorless gas (CO_2)—**carbonates.**

Colorless gas with disagreeable odor (H_2S)—**some sulfids.**

Colorless, pungent gas (Cl) with HCl—**manganese dioxid.**

Brown red, pungent gas (NO_2) with HNO_3—**sulfids** and some elements.

Color of Solution.

Amber solution—**iron** compounds.

Green solution—**copper** (especially when iron is present) and **nickel** compounds.

Blue solution—**copper** compounds.

Pale red solution—**cobalt** compounds.

Insoluble Residue.

Gelatinous residue or slimy silica—some **silicates.**

White residue ($PbSO_4$), ($HSbO_3$), (AgCl)—**lead, antimony,** and **silver** minerals.

Yellow residue (WO_3)—**calcium tungstate.**

XVI. Wet Tests and Group Reagents.

A. Wet Tests for Metals (Cations)

HCl precipitates AgCl, HgCl, and $PbCl_2$.

H_2S in acid solutions precipitates Ag_2S, PbS, HgS + Hg, Bi_2S_3, CuS, HgS, As_2S_3, As_2S_3 + S, Sb_2S_3, SnS, and SnS_2.

NH_4OH in the presence of HCl (or NH_4Cl) precipitates $Pb(OH)_2$, Hg_2NH_2Cl, $Hg\,NH_2Cl$, $BiO(OH)$, $SbO(OH)$, $Sn(OH)_2$, $Sn(OH)_2$, $Al(OH)_4$, $Cr(OH)_3$, $Fe(OH)_3$, $Fe(OH)_2$, and also $Ca_3(PO_4)_2$, CaF_2, and $Ca(BO_2)_2$.

$(NH_4)_2S$ in neutral solutions precipitates Ag_2S, PbS, HgS, CuS, Bi_2S_3, Sb_2S_3, SnS, $Al(OH)_3$, $Cr(OH_3)$, FeS, FeS + S, ZnS, MnS, CoS, and NiS.

$(NH_4)_2CO_3$ precipitates, from alkaline solutions, carbonates of all the non-alkali metals except Mg. With Ag, Cu, Co, Ni, and Zn the precipitate is soluble in excess.

Na_2HPO_4 precipitates all the metals except the alkalies as phosphates, Hg as basic chlorid, and Sb as oxid.

Na_2CO_3 precipitates all the metals except the alkalies as follows: Ag_2CO_3, Hg_2CO_3, $CdCO_3$, $FeCO_3$, $MnCO_3$, $BaCO_3$, $SrCO_3$. $CaCO_3$, $MgCO_3$, $Fe(OH)_3$, $Al(OH)_3$, $Cr(OH)_3$, $Sn(OH)_2$, H_2SnO_3, Sb_2O_3, Hg_2OCl_2, H_3SbO_4, and basic carbonates of Pb, Cu, Zn, Co, and Ni.

H_2SO_4 (dilute) precipitates $PbSO_4$, $BaSO_4$, $SrSO_4$, $CaSO_4 \cdot 2H_2O$ (incompletely unless alcohol is added), and $HgSO_4$ (incompletely).

NaOH precipitates Ag_2O, Hg_2O, HgO, $Cu(OH)_2$, $Cd(OH)_2$, $BiO(OH)$, $SbO(OH)_3$, $Sn(OH)_2$, $SnO(OH)_2$, $Fe(OH)_3$, $Fe(OH)_2$, $Ni(OH)_2$, $Co(OH)_2$, $Mn(OH)_2$, $Ba(OH)_2$ (incompletely), $Sr(OH)_2$ (incompletely), $Ca(OH)_2$ (incompletely), $Mg(OH)_2$, and the following which are soluble in excess: $Pb(OH)_2$, Sb_2O_3, $SbO(OH)_3$, $Sn(OH)_2$, $SnO(OH)_2$, $Al(OH)_3$, $Cr(OH)_3$, $Zn(OH)_2$.

$(NH_4)_2C_2O_4$ precipitates oxalates of all the metals except the alkalies and magnesium from alkaline solutions.

B. Wet Tests for Acid Radicals (Anions)

With $BaCl_2$ as a reagent.

A white ppt. insoluble in HCl indicates **SO_4**.

A white ppt. soluble in HCl, but insoluble in acetic acid indicates **F**.

A yellow ppt. soluble in HCl but insoluble in acetic acid indicates **CrO_4**.

A white ppt. soluble in HCl and in acetic acid indicates **BO_2** or **B_4O_7**, **PO_4**, **CO_3**, or **AsO_4**.

With $AgNO_3$ as a reagent.

A yellow ppt. soluble in HNO_3 indicates **PO_4**.

A red or red-brown ppt. soluble in HNO_3 indicates **AsO_4** or **CrO_4**.

A white ppt. soluble in HNO_3 indicates **BO_2** or **B_4O_7**.

A white ppt. insoluble in HNO_3 indicates **Cl**.

A black ppt. soluble in HNO_3 indicates **S**.

XVII. Preparation of Solution.

Water is the first solvent used, and after that either hydrochloric or nitric acids. For some minerals HCl is the best solvent and for some HNO_3 is the best; therefore it is well to try a small quantity of the mineral with each of these solvents to determine which is the better. For sulfids HNO_3 is the best solvent, but if either lead, antimony, or tin is present, white residues are formed. HCl will precipitate chlorids of silver, lead, and mercury. If the substance is insoluble in both HNO_3 and HCl it may be soluble in aqua regia (1 part HNO_3+3 parts HCl).

Many minerals, especially silicates, are insoluble in aqua regia, and require fusion with Na_2CO_3 on platinum foil or in a porcelain crucible. A water solution of the fusion will generally contain sodium salts of various acids, while an acid solution of the residue will generally contain the metals.

The following minerals are not decomposed by Na_2CO_3 and

require fusion with KOH in a nickel or silver crucible: corundum, (Al_2O_3), cassiterite, (SnO_2), and rutile, (TiO_2).

XVIII. Qualitative Scheme. (For the more common elements).

HCl Group.

1. Add cold dilute HCl in excess. Ppt. 2. Filtrate 6.
2. Wash ppt. with hot water on filter-paper. Residue 3. Filtrate 5.
3. Add NH_4OH to residue drop by drop. A blackening indicates **Hg.** Divide filtrate into two portions 4 and 5.
4. Acidify filtrate with HNO_3. A white ppt. indicates **Ag.**
5. Test filtrate with K_2CrO_4. A yellow ppt. indicates **Pb.**

H_2S Group.

6. Pass H_2S into warm, slightly acid solution. Ppt. 7. Filtrate 16.
7. Digest ppt. with $(NH_4)_2S$. Filter. Residue 8. Filtrate 13.
8. Digest residue with hot dilute HNO_3. Filter. Residue 9. Filtrate 10.
9. Dissolve residue in aqua regia. Boil off Cl. A ppt. with $SnCl_2$ indicates **Hg.**
10. Add a little conc. H_2SO_4 and drive off excess. A white ppt. indicates **Pb.** Filtrate 11.
11. Add NH_4OH in excess to filtrate. A white ppt. indicates **Bi.** Filtrate 12.
12. A blue filtrate indicates **Cu.** Add KCN until blue color disappears; then pass H_2S. A yellow ppt. indicates **Cd.**
13. Add dilute HCl to filtrate. Heat ppt. formed with conc. HCl. A residue indicates **As.** Filtrate 14.
14. Into the dilute solution, heated to almost boiling, pass H_2S. An orange red ppt. indicates **Sb.** Filtrate 15.
15. Into the cool diluted filtrate pass H_2S. A yellow ppt. indicates **Sn.**

NH_4OH Group.

16. Boil off H_2S, add a few drops of HNO_3. Add NH_4Cl and NH_4OH. Ppt. 17. Filtrate 22.
17. Dissolve ppt. in least possible amount of HCl. Add 50% alcohol and dilute H_2SO_4. A crystalline ppt. indicates **Ca.** Filtrate 18.
18. Boil off the alcohol, make filtrate alkaline with NH_4OH. Ppt. 19. Reject filtrate.
19. Fuse ppt. with Na_2CO_3 and $NaNO_3$ on platinum foil. A bluish-green mass indicates **Mn.** Digest the fused mass in hot water and filter. Residue indicates **Fe.** Divide filtrate into two portions, 20 and 21.
20. A yellow filtrate giving red ppt. with $AgNO_3$ indicates **Cr.**
21. Acidify with HCl. Add solid NH_4Cl and boil. A ppt. indicates **Al.**

$(NH_4)_2S$ Group.

22. Into the warm alkaline filtrate pass H_2S. Ppt. 23. Filtrate 29.

23. Wash ppt. on filter with cold dilute (1 : 10) HCl. Residue 24. Filtrate 26.

24. Dissolve residue in aqua regia. Evaporate to dryness, add a little water, and make strongly basic with NaOH. Add tartaric acid but not enough to make the solution acid. Heat slightly and pass H_2S. A ppt. indicates **Co**. Filtrate 25.

25. Acidify filtrate with HCl. A ppt. indicates **Ni**.

26. Boil filtrate to remove H_2S. Add KOH in excess. Ppt. 27. Filtrate 28.

27. Fuse ppt. with Na_2CO_3. A bluish-green mass indicates **Mn**.

28. Add H_2S to the filtrate and heat. A white ppt. indicates **Zn**.

$(NH_4)_2CO_3$ Group.

29. Evaporate filtrate to rather small volume. Add $(NH_4)_2CO_3$ and alcohol. After standing an half-hour, filter. Ppt. 30. Filtrate 34.

30. Dissolve ppt. in hot dilute acetic acid and add K_2CrO_4. A yellow ppt. indicates **Ba**. Filtrate 31.

31. Add NH_4OH and alcohol. A yellow ppt. indicates **Sr**. Filtrate 32.

32. Dilute and add $(NH_4)_2C_2O_4$. A white ppt. indicates **Ca**. Filtrate 33.

Alkal Group.

33. Add NH_4OH and Na_2HPO_4. A white ppt. indicates **Mg**.

34. Evaporate filtrate to dryness. Ignite to drive off ammonium salts. Add NaOH and Na_2HPO_4. Heat and add alcohol. A white ppt. indicates **Li**. Filtrate 5.

35. To the filtrate add $Na_3Co(NO_2)_6$. A yellow ppt. indicates **K**.

Note.—The original substance must be tested for **Na** and **NH_4**.

4. SELECT BLOWPIPE AND WET TESTS

Aluminum, Al.

1. Infusible aluminum minerals (also zinc silicates) when heated intensely before and after adding cobalt nitrate solution give a fine blue color. Fusible minerals may give a blue cobalt glass whether aluminum is present or not.

2. Ammonium hydroxid gives a white gelatinous precipitate, $Al(OH)_3$, in solutions containing aluminum. (The ppt. is soluble in KOH or NaOH.) Iron hydroxid, chromium hydroxid, calcium phosphate, calcium borate, and calcium fluorid are also precipitated by NH_4OH along with $Al(OH)_3$. The calcium may

be removed by means of dilute sulfuric acid and 50 per cent. ethyl alcohol before testing for iron and aluminum.

Antimony, Sb.

1. Antimony minerals heated on charcoal in O.F. give a volatile white sublimate (Sb_2O_4) near the assay and dense white fumes without odor.

2. With iodid flux on a plaster tablet antimony compounds give a peach-red coating or an orange coating stippled with peach-red.

3. In the open tube antimony minerals give a non-volatile, amorphous, white sublimate (Sb_2O_4) on the under side of the tube.

4. Compounds of antimony and sulfur give a reddish-brown sublimate (Sb_2S_2O) when heated intensely in the closed tube.

5. Concentrated HNO_3 oxidizes antimony sulfids and sulfosalts to $HSbO_3$, a white precipitate soluble in KOH.

Arsenic, As.

A. Compounds without Oxygen.

1. On charcoal most arsenic minerals give a white volatile coating (As_2O_3) far from the assay and fumes with characteristic odor of arsin (AsH_3) (a disagreeable odor something like that of garlic).

2. In the open tube, minute, brilliant, colorless crystals (As_2O_3). This sublimate is volatile in contrast with that of Sb_2O_4.

3. In the closed tube a black metallic mirror of arsenic. A gray crystalline sublimate may also form.

4. H_2S precipitates yellow As_2S_3, which is soluble in $(NH_4)_2S_x$, but insoluble in concentrated HCl.

B. Arsenates.

5. Arsenates heated intensely in the closed tube with charcoal give a black metallic mirror of arsenic.

6. Nitric acid solutions of arsenates give a yellow precipitate with $(NH_4)_2MoO_4$ when heated to boiling.

If the solution is to be tested for a phosphate, the arsenic must be removed by means of H_2S (see 4).

Barium, Ba.

1. Yellowish-green flame (not made blue by HCl).

2. Dilute H_2SO_4 precipitates white $BaSO_4$, a finely divided precipitate insoluble in acids. This, like strontium sulfate, forms in very dilute solutions while calcium sulfate forms only in fairly concentrated solutions.

3. $(NH_4)_2CO_3$[or $(NH_4)_2C_2O_4$] gives a white precipitate soluble in acids. (Sr and Ca also.)

4. K_2CrO_4 (or $K_2Cr_2O_7$) gives a yellow precipitate (distinction from Sr and Ca).

Beryllium, Be.

1. $Be(OH)_2$ is precipitated along with $Al(OH)_3$ by NH_4OH. The precipitate is dissolved in dilute HCl and the solution evaporated nearly to dryness. A little water is added, and also KOH in amount sufficient to dissolve the precipitate which forms at first. The solution is diluted and boiled when $Be(OH)_2$ separates out. This precipitate heated on charcoal with cobalt nitrate solution assumes a lavender color.

Bismuth, Bi.

1. With iodid flux on plaster, a purplish-chocolate sublimate with underlying scarlet.

2. With sodium carbonate on charcoal in R.F., a metallic button brittle on the edges, and also a yellow sublimate (BiO).

3. To a nitric acid solution from which the excess of acid has been evaporated, HCl is added. On dilution with water, a white precipitate of bismuth oxychlorid (BiOCl) is formed.

Boron, B.

1. Borates give a green flame, especially if moistened with H_2SO_4. Silicates containing boron give a momentary green flame when heated with boric acid flux (3 parts $KHSO_4$ to 1 part powdered fluorite, CaF_2). This flame is due to the formation of volatile BF_3.

2. Alcohol added to a solution of a borate will burn with a green flame.

3. Turmeric paper moistened with a HCl solution of a borate, and dried carefully on the outside of the test-tube containing the boiling solution, becomes reddish-brown. This color is changed to black by NH_4OH. It is well to run a blank test at the same time. Zirconium solutions give a similar test.

Calcium, Ca.

1. In a rather concentrated solution, dilute H_2SO_4 precipitates $CaSO_4 \cdot 2H_2O$, which appears crystalline with the hand lens in contrast with $BaSO_4$ and $SrSO_4$. The addition of 50 per cent. ethyl alcohol makes a very complete precipitation.

FIG. 4.—Microchemical gypsum.

2. The microchemical gypsum test is the most satisfactory test for calcium. A drop of solution containing calcium is placed on a glass slip and alongside of it a drop of dilute H_2SO_4. The two drops are brought into contact. In a few minutes time small crystals of $CaSO_4 \cdot 2H_2O$ (gypsum) make their appearance. (See Fig. 4.)

3. Yellowish-red flame with HCl.

4. $(NH_4)_2C_2O_4$ or $(NH_4)_2CO_3$ gives a white precipitate soluble in acids, as do also Ba and Sr. (Ba gives a yellow precipitate with K_2CrO_4 in the presence of dilute acetic acid. $Ca(NO_3)_2$ is soluble in ether-alcohol, while $Sr(NO_3)_2$ is insoluble.)

5. Calcium borates, fluorids, and phosphates are all precipitated from acid solution on the addition of NH_4OH, and hence may be confused with aluminum hydroxid. In this case the calcium may be detected as given in Note 1 above.

Carbon, C.

A. Carbonates

1. Carbonates effervesce in dilute acids (some in the cold, others only upon heating) with the evolution of a colorless, odor-

less gas which gives a white precipitate with $Ba(OH)_2$ or lime-water.

2. Carbonates effervesce in a hot borax bead. When the bead cools, a mass of tiny bubbles may be detected with a lens.

3. Citric acid, a solid, serves as a convenient field reagent. Carbonates effervesce in a water solution of citric acid.

B. Hydrocarbons

1. Hydrocarbons, such as asphaltum, albertite, bituminous coal, etc., which are mineraloids rather than true minerals, when heated in the closed tube give oils and tar-like substances with a characteristic disagreeable odor.

Chlorin, Cl.

1. To a $NaPO_3$ bead saturated with CuO (or malachite) a little of the powdered substance is added. On heating, an intense azure-blue flame is obtained.

2. Insoluble chlorids fused first with Na_2CO_3, and then heated with MnO_2 and an excess of $KHSO_4$ in a closed tube, give free chlorin.

3. In chlorid solutions $AgNO_3$ gives a white curdy precipitate which is soluble in NH_4OH.

Chromium, Cr.

1. The borax and sodium metaphosphate beads are emerald green in both O.F. and R.F.

2. The sodium carbonate bead is yellow in O.F. A little KNO_3 or $NaNO_3$ helps the reaction.

3. Chromate solutions give a dark red precipitate with $AgNO_3$ and a yellow precipitate with $Pb(C_2H_3O_2)_2$.

Cobalt, Co.

1. The borax and sodium metaphosphate beads are deep blue in both O.F. and R.F. This furnishes a very delicate test for cobalt.

2. Heated on charcoal in R.F., cobalt compounds become magnetic as do also nickel and iron compounds.

Copper, Cu.

1. Green flame made azure-blue with HCl.

2. Borax and sodium metaphosphate beads are blue in O.F., and opaque red (due to Cu_2O) in R.F. if large amounts are used. Metallic copper may also be formed in R.F. In the presence of iron, the O.F. bead is green or bluish-green.

3. On charcoal with Na_2CO_3 in R.F., and also with $NaPO_3$ and metallic tin on charcoal, metallic copper (malleable) is obtained.

4. Solutions of copper minerals are blue (green in the presence of iron). NH_4OH in excess produces a deep blue coloration. (Nickel solutions give a faint blue coloration with NH_4OH.)

5. A slightly acid copper solution touched to a bright surface of iron, such as knife-blade or hammer, gives a coating of metallic copper.

Fluorin, F.

1. Fluorids are soluble in concentrated H_2SO_4 with evolution of HF which etches glass. A lead dish, or watch-glass coated with paraffin, should be used.

2. Fluorin compounds heated in a closed tube with 4 parts of $NaPO_3$ will etch glass, and deposit a ring of SiO_2 which cannot be washed off with water.

3. Fluorin compounds heated with concentrated H_2SO_4 and powdered silica give fumes which condense on moistened black paper.

4. Fluorids give a momentary green flame when heated with borax and $KHSO_4$. This flame is due to the formation of volatile BF_3.

Gold, Au.

1. With sodium carbonate on charcoal, gold compounds give a malleable yellow button.

2. Gold may be identified in some of its rich ores by panning and washing away light quartz, rock, etc. Mercury is added to

the concentrates. By grinding in a mortar, an amalgam of gold is obtained. This may be heated on charcoal or in a closed tube, and the mercury driven off. When the residue is heated with a little borax on charcoal a globule of gold is obtained.

Hydrogen, H.

1. Minerals with so-called water of crystallization give water when heated in a closed tube at a comparatively low temperature (100–150° C.). With hydrous sulphates of iron, copper, and aluminum the water has an acid reaction which is due to the SO_3 given off.

2. Acid salts and basic salts give water at comparatively high temperatures (usually above 150° C.).

Iron, Fe.

1. On charcoal in R.F., especially with sodium carbonate, iron minerals become magnetic. (This test must be tried after the assay has become cold.) Cobalt and nickel compounds give a similar test.

2. In O.F. the borax bead is amber colored, and in R.F., pale green.

3. NH_4OH precipitates brownish-red $Fe(OH)_3$ from solutions containing ferric iron. A few drops of HNO_3 should always be added to the solution to insure oxidation of the iron to the ferric condition.

4. To detect state of the iron, a borax bead made blue with CuO (or malachite) is changed to opaque red by a ferrous compound, and to green by a ferric compound. (Use a neutral flame.)

5. To detect the state of iron in insoluble minerals (especially silicates), fuse powdered mineral with a large excess of borax in a test-tube. Break the tube and dissolve finely powdered contents in HCl. Divide the solution in two portions and test one with $K_4Fe(CN)_6$ (ferric compounds give a deep blue precipitate) and the other with $K_3Fe(CN)_6$ (ferrous compounds give a dark blue precipitate).

Lead, Pb.

1. On charcoal with sodium carbonate in R.F. a malleable button of lead and a yellow coating of PbO. PbS also gives a white coating of $PbSO_4$

2. On plaster with iodid flux, lead compounds give a lemon-yellow coating.

3. From nitric acid solutions containing lead, HCl precipitates $PbCl_2$, which is soluble in the hot solution, but recrystallizes on cooling the solution as white acicular crystals with adamantine luster.

Lithium, Li.

1. A purplish-red flame, most intense at first.

2. For separation from the other alkalies, see item 34, page 40.

Magnesium, Mg.

1. In the presence of NH_4OH and NH_4Cl, Na_2HPO_4 precipitates $NH_4MgPO_4 \cdot 6H_2O$, which forms slowly. The solution should be cold. Other metals (except alkalies) must be absent as they also give precipitates.

2. White magnesium compounds give a pink color when ignited with cobalt nitrate solution. (This test is not very satisfactory).

Manganese, Mn.

1. The sodium carbonate bead is bluish-green and opaque (a very delicate test).

2. The borax or $NaPO_3$ bead is amethyst colored in O.F. and colorless in R.F. Large amounts of iron interfere with this test.

3. With HCl manganese dioxids give off chlorin, a gas recognized by its penetrating odor.

Mercury, Hg.

1. In closed tube with *dry* sodium carbonate, mercury compounds give metallic globules of mercury.

2. On plaster with iodid flux a scarlet sublimate when gently heated. If overheated, the sublimate is dark greenish-yellow.

3. Most mercury compounds rubbed on a copper coin with HCl give a white amalgam.

Molybdenum, Mo.

1. The $NaPO_3$ bead is green in R.F., but colorless in O.F. Several R.F. beads dissolved in HCl with tin give a brown solution.

2. Na_2HPO_4 gives a yellow precipitate with hot nitric acid solutions of molybdenum compounds.

Nickel, Ni.

1. The borax bead in O.F. is violet when hot, reddish-brown, when cold; while in R.F. the bead is turbid gray.

2. With nickel solutions NaOH gives a pale green precipitate which is insoluble in excess. With NH_4OH a precipitate is formed which is soluble in excess to a pale blue solution (fainter than copper).

3. A one per cent. solution of dimethyl-glyoxime in alcohol added to an alkaline solution containing nickel, will give a red precipitate.

Niobium, Nb.

1. When fused with borax and then dissolved in HCl, the addition of metallic tin gives a deep blue solution similar to that obtained for tungsten; but, unlike the latter, the color disappears on the addition of water.

Nitrogen, N.

1. In the closed tube with $KHSO_4$, nitrates give brown-red fumes of NO_2.

2. A concentrated solution of $FeSO_4$ added to a solution of a nitrate in concentrated H_2SO_4 gives a brown ring.

Oxygen, O.

No direct tests for oxygen are easily made. The dioxids of manganese dissolve in HCl with the evolution of chlorin, which is recognized by its odor and by its bleaching effect on litmus paper.

Phosphorus, P.

1. An excess of $(NH_4)_2MoO_4$ added to a hot nitric acid solution of a phosphate gives a yellow precipitate which is soluble in NH_4OH. The solution should be only slightly heated, for arsenates give a similar precipitate on boiling.

2. Most phosphates give a bluish-green flame when moistened with H_2SO_4.

Platinum, Pt.

1. Metallic platinum is insoluble in any single acid, but soluble in aqua regia. In rather concentrated, slightly acid solutions, KCl gives a yellow precipitate, K_2PtCl_6, insoluble in alcohol.

Potassium, K.

1. Violet flame, masked by sodium, but visible through a blue glass. (Merwin's flame-color screen is better than a blue glass.) Potassium in silicates may be detected by fusing with Na_2CO_3 and observing the flame through a blue glass or screen.

2. Sodium cobaltic nitrite, $Na_3Co(NO_2)_6$, (see p. 25), gives a yellow precipitate insoluble in alcohol.

3. With H_2PtCl_6, potassium solutions give a yellow crystalline precipitate (K_2PtCl_6) insoluble in 95 per cent. alcohol.

Silicon, Si.

1. In the $NaPO_3$ bead, silica and the silicates are partially dissolved and usually leave a translucent mass or skeleton of SiO_2. (A few other minerals such as corundum are soluble with difficulty.)

2. With a small amount of sodium carbonate, silica effervesces and forms a clear mass. The equation is: $Na_2CO_3 + SiO_2 = Na_2SiO_3 + CO_2$.

3. Some silicates dissolve in HNO_3 or HCl, and on evaporation leave either a gelatinous mass or a slime of silicic acid.

4. For insoluble silicates a sodium carbonate fusion must be made. The finely powdered mineral is fused on platinum foil,

or a spiral loop of platinum wire, with three to four parts of sodium carbonate. The fused mass is dissolved in dilute HNO_3 and carefully evaporated just to dryness. After adding dilute HCl and boiling, the insoluble silica is filtered off. The filtrate contains the metals, which are commonly Al, Fe, Ca, and Mg. The following is a scheme of separation:

Add NH_4OH and NH_4Cl (boiling)	$Fe(OH)_3, Al(OH)_3$: $Al(OH)_3$ is soluble in KOH.	
	Add $(NH_4)_2C_2O_4$ (hot)	CaC_2O_4.
		Add Na_2HPO_4 (cold) $MgNH_4PO_4 \cdot 6H_2O$.

5. For the detection of alkalies in silicates, the *very finely* powdered substance is intimately mixed with five parts of $CaCO_3$ and one part of NH_4Cl and fused for some time on platinum foil. The sintered mass is digested in hot water and filtered. NH_4OH and $(NH_4)_2CO_3$ are added to the filtrate. The precipitate is filtered off and the filtrate evaporated to dryness. The residue is ignited until all the ammonium salts are volatilized, and then the residue is dissolved in a little water. On the addition of H_2PtCl_6 and 95 per cent. alcohol, a yellow precipitate indicates K. The filtrate is evaporated to dryness and the flame tested for Na.

Silver, Ag.

1. With soda on charcoal in R.F., silver minerals yield malleable metallic globules of silver, which may be tested as under 3.

2. For the blowpipe silver assay see page 34.

3. On the addition of HCl nitric acid solutions of silver minerals give a white curdy precipitate which changes to violet on exposure to light and is soluble in NH_4OH.

Sodium, Na.

1. Intense yellow flame masked by a thick blue glass (or Merwin flame-color screen). This is such a delicate test that only an intense and prolonged coloration indicates sodium as an essential constituent.

2. Sodium in insoluble silicates may be detected by the method given under Silicon, note 5.

Strontium, Sr.

1. Strontium compounds give a crimson flame, especially with HCl.

2. Dilute H_2SO_4 gives a white precipitate, $SrSO_4$, with dilute strontium solutions. Barium solutions give the same test, and may be distinguished by the fact that K_2CrO_4 precipitates $BaCrO_4$ from an acetic acid solution while the strontium remains in solution.

Sulfur, S.

A. Sulfids and Sulfo-salts.

1. The finely powdered substance fused with three parts of sodium carbonate on a sheet of mica (or platinum foil) gives a mass which stains a moistened silver coin. Tellurids and selenids give the same test.

2. In the closed tube some sulfids (*e.g.* pyrite) give a yellow sublimate of sulfur.

3. In the open tube sulfids give off SO_2, a colorless gas with the odor of burning matches.

4. A few sulfids (*e.g.*, sphalerite) dissolve in HCl with the evolution of H_2S.

5. Sulfids are oxidized to sulfates by nitric acid with the evolution of brown-red fumes of NO_2. The solution may be tested as under 7 below.

B. Sulfates.

6. A sulfate, powdered and thoroughly mixed with 3 parts of soda and a little charcoal powder, is fused on charcoal in R.F. The fused mass will stain a moistened silver coin. Sulfids give the same test, so it is necessary to try the test on mica or platinum first.

7. Sulfate solutions with $BaCl_2$, give a white precipitate which is insoluble in HCl. If the mineral is insoluble in acids it must

be fused with Na_2CO_3, and the water solution of the fusion used.

8. Sulfate solutions will give the microchemical gypsum test with a calcium salt (calcite dissolved in HCl is convenient). See Calcium, note 2, page 43.

Tellurium, Te.

1. A powdered tellurid added to hot concentrated H_2SO_4 gives a fine red-violet coloration.

2. Tellurids give a pale bluish-green flame coloration and a white sublimate on charcoal.

3. On plaster with bismuth flux, a purplish sublimate is obtained with tellurids. (Like that for bismuth except that there is no underlying scarlet.)

Tin, Sn.

1. Cassiterite, wrapped in zinc shavings or placed on a sheet of zinc, and treated with dilute HCl becomes coated with metallic tin.

2. Tin compounds heated on charcoal in O.F. give a straw-colored coating, SnO_2. On addition of $Co(NO_3)_2$ solution and heating in R.F., a bluish-green coloration results.

3. Tin compounds fused on charcoal with sodium carbonate and a little sulfur in strong R.F. give malleable metallic buttons of tin which are oxidized by HNO_3 to a white insoluble powder, H_2SnO_3.

Titanium, Ti.

1. The $NaPO_3$ bead saturated with the finely powdered mineral is violet in R.F. and colorless in O.F.

2. Fused with Na_2CO_3, dissolved in HCl, and the solution heated with metallic tin, titanium compounds give a violet-colored solution due to the formation of $TiCl_3$. The solution is usually turbid due to the formation of metatitanic acid, H_2TiO_3.

3. A yellow coloration results when a solution of hydrogen peroxide is added to the substance fused with $KHSO_4$. This is a very delicate test.

Tungsten, W.

1. The $NaPO_3$ bead is blue in R.F., colorless in O.F. Iron interferes and gives a red bead in R.F.

2. $NaPO_3$ beads treated on charcoal in R.F. with tin are dissolved in HCl and on the addition of metallic tin, a deep blue solution results. Niobates give a similar test but the blue coloration disappears on the addition of water in this case.

3. With soluble tungstates HCl gives a yellow residue, WO_3, which is soluble in NH_4OH. On the addition of tin and boiling, the precipitate becomes blue.

Uranium, U.

1. The $NaPO_3$ bead is a fine green in R.F. and yellowish-green in O.F.

Vanadium, V.

1. The $NaPO_3$ bead is a fine green in R.F.; light yellow in O.F.

2. In the closed tube with $KHSO_4$, vanadates give a yellow mass.

Water (see Hydrogen).

Zinc, Zn.

1. On charcoal with sodium carbonate, zinc compounds give a white coating which is yellow when hot. With silicates the addition of borax helps.

2. Zinc minerals, when moistened with $Co(NO_3)_2$ solution and intensely ignited, assume a bright green color which is due to the formation of cobalt zincate. Zinc silicates give a blue color like aluminum compounds, but if tried on charcoal the sublimate will turn green.

3. $(NH_4)_2S$ precipitates ZnS in alkaline solutions which is remarkable as being the only insoluble white sulfid.

Zirconium, Zr.

1. An HCl solution of a soda fusion turns turmeric paper orange color. This test is like that for a borate, the absence of which must be proved.

THE MORPHOLOGICAL PROPERTIES OF MINERALS

Minerals may occur in two essentially different conditions or states: (1) the crystalline and (2) the amorphous. In a crystalline substance many of the physical properties such as cleavage and hardness, for example, vary with the direction, while on the other hand, in an amorphous substance the physical properties are the same in all directions. Of the various directional or vectorial properties, some vary continuously and can be represented by a curve, while the others have sharp breaks and so are called discontinuous. (See Figs. 299 and 300 on page 148.)

A crystalline substance is a homogeneous substance with discontinuous vectorial properties (Friedel.) Cleavage is one of the prominent discontinuous vectorial properties. Crystalline substances when formed under favorable conditions in a free space usually take on a geometric form characteristic of the substance. Such crystals are said to be **euhedral.** Rock crystal (quartz) furnishes a good example. An irregular fragment of quartz is still a crystal, for it has exactly the same physical and chemical properties as the perfect geometric form. A crystal without external faces is said to be **anhedral,** while crystals with imperfectly developed faces are said to be **subhedral.** These terms are necessary in order to avoid the ambiguity in the use of the term crystal.

1. THE AMORPHOUS CONDITION

Amorphous substances in free spaces assume a more or less spherical form. In this respect they resemble liquids, for the shape of a liquid free from external influences is spherical. For example, olive oil in a mixture of alcohol and water of exactly the same specific gravity takes on the form of spheres. A variety of opal from Tateyama, Japan, occurs in small spheres. But in most cases amorphous minerals formed in free spaces are in-

fluenced by gravity and for this reason they appear in mammillary (hemispherical protuberances), botryoidal (more or less separated spheres like a bunch of grapes), and stalactitic (pendant like icicles) forms. **Colloform** is a general term coined by the author to cover all these forms. A colloform structure is also assumed by microcrystalline minerals such as chalcedony. The forms assumed by all amorphous minerals are practically the same, while on the other hand the crystals of each mineral are characteristic of that mineral. The amorphous minerals are hardened hydrogels; all are probably colloidal in origin. (See p. 17.)

2. THE GENERAL PROPERTIES OF CRYSTALS

In beginning the study of crystals, the student's attention may be directed to crystals of the common minerals such as calcite (Figs. 158–169), quartz (Figs. 180–183), pyrite (Figs. 113–120), gypsum (Figs. 224–227), and orthoclase (Figs. 212–215). Then, for the time neglecting how they were formed and what they are composed of, their form or geometrical properties may be considered.

Euhedral crystals are naturally formed solids bounded by flat, more or less smooth surfaces called **faces,** which are the result of an internal structure. (The surfaces on cut gems are known as facets.) Intersections of two faces are called **edges,** and intersections of three or more faces are called **vertices.** The faces of crystals vary greatly in number, in shape, and in position. On many crystals it will be noticed that there are several kinds of faces. All the faces of one kind on a crystal constitute a **form.** For example, in Fig. 13 the top and bottom six-sided faces constitute one form, and the six rectangular faces another form. Some crystals have only a single form, but most of them are **combinations** of two or more forms. It is the great number of combinations possible that gives the variety to crystals, for there is practically no limit to the number of forms possible on a crystal.

The arrangement of crystal faces in belts of planes with parallel intersection edges called **zones** is a notable feature of most crystals. For example, the six faces of Fig. 37 constitute a zone.

One of the most striking and important properties of crystals is the recurrence of the faces, edges, and vertices according to some fixed law. This property is known as **symmetry.** It varies for different kinds of crystals, and is the basis for the classification of crystals.

On looking over a number of crystals one might fail to see any order, system, or regularity so great is their variety, and might decide that crystals are fortuitous solids. But such is not the case; for between the faces, angles, and zones of crystals there exist exact mathematical relations. Given the angles between a few faces of a crystal, the angles between any two of the many crystal faces possible may be calculated. Crystal faces intersect only at certain definite angles. A facet cut at random on a crystal is not a crystal face, for the faces are the result of a definite internal structure.

The practical importance of crystallography lies in the fact that a given mineral or artifically prepared compound often occurs in crystals characteristic of that substance, and hence the crystal form may be used in the determination of the substance.

3. THE MEASUREMENT OF CRYSTALS

The angles on any crystal are the plane angles of the faces, the interfacial or dihedral angles over the edges, and the solid or polyhedral angles at the vertices. On account of the difficulty of accurate measurement, the plane angles, though characteristic, are little used. The measurement of interfacial angles is the starting-point in the description and determination of crystals. An **interfacial angle** (dihedral angle of geometry) is defined by the plane angle that is formed by cutting a plane normal to the intersection edge of the two faces. It will be noticed that there are two possible angles to measure: an internal and an external or

supplement angle. For various reasons[1] the supplement angle is the one used in crystallography. In a hexagonal prism, for example, the interfacial angle is read 60° instead of 120°. The interfacial angle may be measured approximately by means of a **contact goniometer,** which, in the simplest type, consists of a semicircular cardboard protractor provided with a celluloid arm (Fig. 5). The plane of the protractor is placed perpendicular to

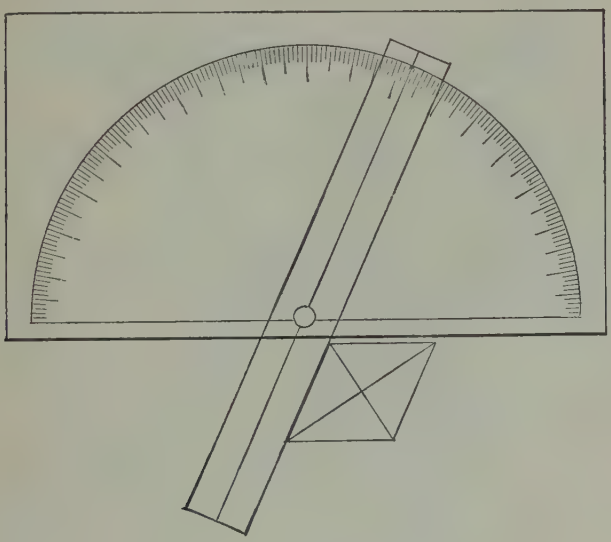


FIG. 5.—Contact goniometer.

the intersection edge. One face of the crystal is brought in contact with the arm and the protractor is revolved until the other face is parallel to, but not quite in contact with, it.

For more accurate work, especially on minute crystals, the **reflection goniometer** is used. The principle of measurement is as follows: if a bright face of a crystal is held close to the eye, a

[1] (1) The sum of the supplement angles in any zone is equal to 360°. (2) The angles obtained directly from the reflection goniometer are the supplement angles. (3) It is easier to estimate the supplement angle with the eye.

reflection of a distant object such as a window bar may be obtained. If the crystal is turned about, reflections are obtained from other faces. The angle through which the crystal is revolved to obtain the images from two adjoining faces is the external or supplement angle.

The reflection goniometer, the invention of Wollaston in 1809, originally consisted of a vertical graduated circle with a horizon-

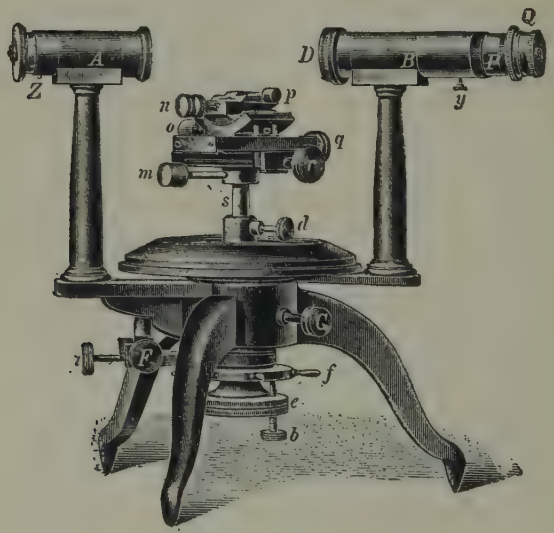


Fig. 6.—Reflection goniometer.

tal axis bearing the crystal carrier. In the modern type of goniometer the graduated circle is horizontal and the axis of revolution is vertical. Fig. 6 shows a convenient type of goniometer for student work. A central axis s bears a crystal carrier (axis of the graduated circle) with adjustments which are two sliding motions (q and r) at right angles, and two tipping motions on circular arcs at right angles (o and n). A collimator A with a biconcave slit at the end, and a telescope B which may be set at any angle to the collimator, complete the equipment. A source

of light, such as a Welsbach burner, placed at the end of the collimator furnishes a beam of light which is reflected from the crystal, when in a certain position, into the telescope. Looking into the telescope one sees a biconcave-shaped image (Fig. 7) which may be bisected by the cross-wires in the telescope. Then the reading on the vernier of the graduated circle is taken. The crystal carrier with the mounted crystal is revolved until an image is reflected from another face, and so on for all faces of the zone. A separate set-up must be made for each zone.

Another type of goniometer is the two-circle or theodolite goniometer which consists of two graduated circles at right angles. Two angles, one corresponding to the longitude and the other to the co-latitude of a place on the earth's surface, are obtained for each face. The advantage of the two-circle goniometer lies in the fact that only one set-up is required for all the faces on one-half of a crystal, but the disadvantage is that in monoclinic and triclinic crystals measurements are not always made in zones.

FIG. 7.—Image obtained with reflection goniometer.

In the case of small crystals with dull faces the polarizing microscope with rotating stage may be used to advantage in measuring angles (see Fig. 332, page 174).

A simple reflection goniometer may be made from the cardboard contact goniometer by fitting a wooden axis through the eyelet, the axis being provided with a wire pointer. Fig. 8 illustrates this device. By holding the goniometer, with the crystal mounted on the end of the axis with wax, so that the intersection edge of the faces is in line with the axis, an image of a distant object, such as a window-bar, on a crystal face is made to coincide with the edge of a table or similar line of reference. The reading of the pointer is taken. Then after obtaining the same image again, the goniometer is held firmly and the axis carrying the crystal is rotated until a similar image

is obtained from an adjacent face. The supplement angle is the difference between the two readings, and so on for other faces of the zone. As the protractor includes but 180°, only part of the zone can be measured at one time.

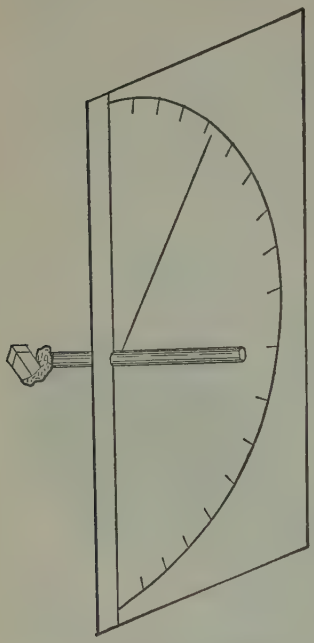


FIG. 8.—Simple reflection goniometer.

4. THE SYMMETRY OF CRYSTALS

The repetition or recurrence of the faces, interfacial angles, and vertices of crystals in accordance with some fixed law is called **symmetry.** Symmetry is perhaps the most important property of crystals, for among natural objects it is a property peculiar to crystals (that is, if the term is used in an exact mathematical sense) and besides furnishes the basis for the classification of crystals. At the same time it should be emphasized that a few crystals lack symmetry of any kind (*e.g.*, hydrous calcium thiosulfate, $CaS_2O_3 \cdot 6H_2O$). (See Fig. 9.)

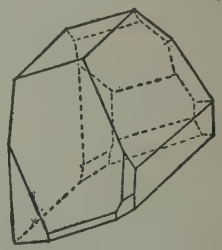


FIG. 9.—A crystal ($CaS_2O_3 \cdot 6H_2O$) devoid of symmetry.

The symmetry of a crystal may be defined by the operations necessary to bring it into coincidence with its original position. The symmetry operations are rotation about an axis, reflection in a plane, a combination of rotation with reflection (rotatory-reflection), and inversion about the center.

If a solid can be revolved about some line through its center so that similar faces recur a certain number of times in a complete revolution, that line is called an **axis of symmetry** (denoted by

$\mathbf{A}_n$). In crystals the period of the axis (the value of n in the symbol $\mathbf{A}_n$) or the number of times of recurrence is either two

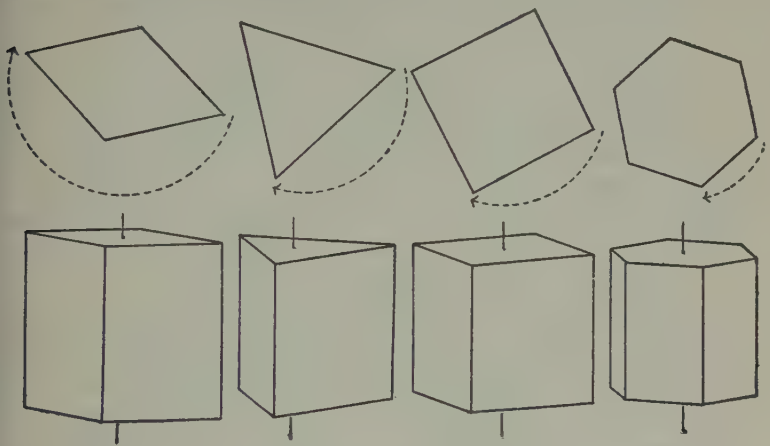


FIG. 10. FIG. 11. FIG. 12. FIG. 13.

Figures illustrating axes of symmetry.

(2), three (3), four (4), or six (6). An axis about which similar faces recur every 180° is said to be a **two-fold axis** ($\mathbf{A}_2$); every 120°, a **three-fold axis** ($\mathbf{A}_3$); every 90°, a **four-fold axis** ($\mathbf{A}_4$); and every 60°, a **six-fold axis** ($\mathbf{A}_6$). Figs. 10, 11, 12, and 13 illustrate these various axes of symmetry. The vertical lines through the centers of the lower figures are the axes of symmetry. The plane figures above are plans showing the amount of rotation necessary to bring the figures into self-coincidence.

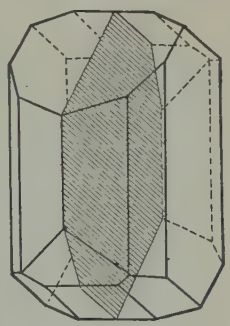


FIG. 14.—Plane of symmetry.

A plane that divides a solid into two parts so that similar faces occur on opposite sides of the plane is called a **plane of symmetry** (denoted by **P**). Unless the crystal is mis-shapen, one half is the mirror image of the other half. Fig. 14 represents an orthoclase

crystal in which the shaded area is a plane of symmetry. The faces are either perpendicular to this plane, or occur in pairs, one on each side of it. A crystal may have a number of planes of symmetry. A cube, for example, has nine, three parallel to opposite faces and six through opposite edges.

A solid is said to have a **center of symmetry** (denoted by **C**) if a line drawn from any point through the center encounters an exactly similar point on the opposite side. The operation is called **inversion.** Figure 15 represents a crystal of axinite with a center of symmetry. Every face has a similar parallel face on the opposite side of the crystal. This is the easiest test for a center of symmetry.

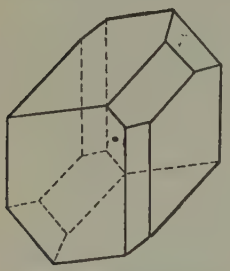


FIG. 15.—Center of symmetry.

The recurrence of similar faces by rotation about an axis, combined with reflection in a plane normal to the axis, is called **composite symmetry.** The two operations, rotation and reflection, take place simultaneously; therefore the symbol $\mathcal{P}_n$ is used. The period of the axis is always even and in crystals the two possible cases are $\mathcal{P}_4$ and $\mathcal{P}_6$. In Fig. 16 the vertical line is an axis of 4-fold composite symmetry, for the upper part of the crystal revolved 90° becomes a reflection of the lower part. Similarly the vertical line in Fig. 17 is an axis of 6-fold composite symmetry, for the crystal revolved 60° becomes a reflection of the lower part.[1] It should be observed that $\mathcal{P}_4$ includes A_2, and $\mathcal{P}_6$ includes A_3, so these may be written $\mathcal{P}_4$ (A_2) and $\mathcal{P}_6$ (A_3).

In Fig. 15 the front part of the crystal when revolved 180° becomes the reflection of the rear part (dotted lines). This is true, however, of any direction in the crystal, so that $\mathcal{P}_2$ becomes $\infty \mathcal{P}_2$. It is more logical to use **C** than $\infty \mathcal{P}_2$, for a single operation (inversion) is involved.

[1] A twin-model of calcite with {0001} as twin-plane may be used to show composite 6-fold symmetry.

Center, axis, plane, and composite axis with plane are collectively known as **elements of symmetry.** In crystals the elements of symmetry are combined in various ways. With the limitation imposed by the rationality of indices, or with the assumption of a crystal structure made up of particles at small, finite distances apart, only axes of 2-, 3-, 4-, and 6-fold symmetry are possible, and in fact no other axes of symmetry have ever been found in crystals. The elements of symmetry, then, are as

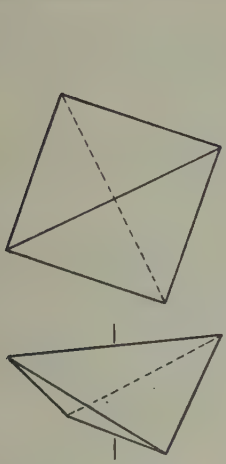


FIG. 16.

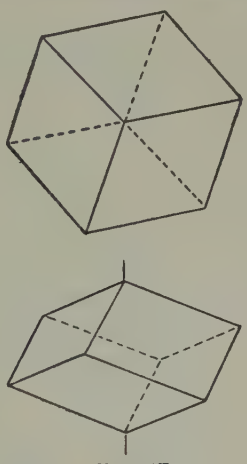


FIG. 17.

Figures illustrating composite symmetry.

follows: A_2, A_3, A_4, A_6, P, C, $\not{A}_4$, and $\not{A}_6$. Various methods of combining the elements of symmetry with each other lead to the result that only thirty-one combinations are possible among crystals. These thirty-one combinations of symmetry elements plus the crystal division without any symmetry constitute the **thirty-two crystal classes.**

In the above discussion the term similar faces has been used so often that an explanation is necessary. By similar faces are meant faces which are more or less alike in shape, size, and appearance. On crystals which have been formed quietly without

disturbing influences, similar faces have the same size and shape. But on account of various external influences similar faces are rarely *exactly* of the same size and shape. The effect of external influences may be illustrated by alum which crystallizes in octahedrons. Alum crystallizing on the bottom of a beaker will form in more or less flattened octahedrons like Fig. 18, while if it crystallizes about a weighted string suspended in the solution, the crystals will be more or less perfect octahedrons like Fig. 19.

The irregularity in the size and shape of similar faces is one difficulty in the study of crystals. While the faces may vary, the

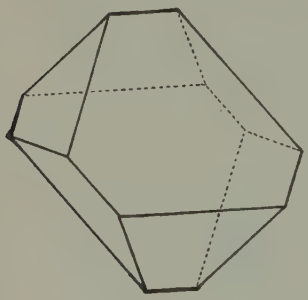


FIG. 18.

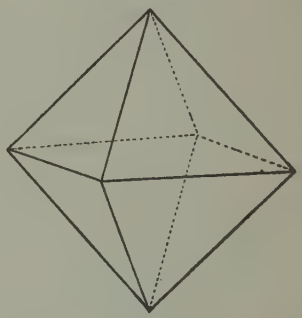


FIG. 19.

Alum crystals.

angles are constant (within certain limits), as is expressed in the law of constancy of interfacial angles: **In all crystals of the same substance, the angles between corresponding faces are constant.** (Steno, 1669.) In order to determine the symmetry of a crystal it is necessary in many cases to measure the interfacial angles. Thus the crystals represented in cross-section by Figs. 20, 21, 22 are bounded by hexagonal prisms and have an axis of six-fold symmetry if the interfacial angles are all 60°. On the other hand, the crystal represented in cross-section by Fig. 23, though apparently a hexagonal prism, is a combination of two forms (a rhombic prism and a pinacoid), and has an axis of two-fold

symmetry and not one of six-fold symmetry because the interfacial angles are 62° and 56° instead of 60°.

Another property of crystals used in determining symmetry is the physical character of the faces; and for this reason geometrical crystallography is by no means merely a branch of geometry. Similar faces are those with the same luster, the same

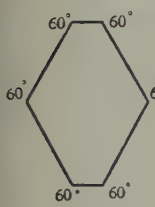


Fig. 20.

Fig. 21.

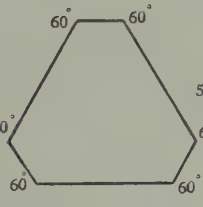


Fig. 22.

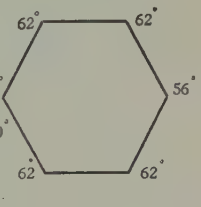


Fig. 23.

kind of striations, pits, or other markings. Geometrically a cube has nine planes of symmetry, three parallel to the cube faces, and six through opposite cube edges, but a cube of pyrite with striations like those of Fig. 24 has only three planes (those parallel to the cube faces). A crystal of sphalerite represented

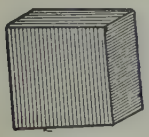


Fig. 24.
Pyrite.

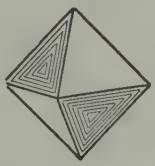


Fig. 25.
Sphalerite.

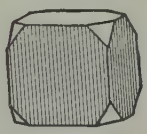


Fig. 26.
Apophyllite.

by Fig. 25 is geometrically an octahedron, but from the standpoint of crystallography it is a combination of two tetrahedrons, one with smooth faces, the other with striated faces. Figure 26 illustrates another good example of this kind. Apophyllite occurs in crystals which are apparently cubes modified by the octahedron. Close examination, however, shows that the side

faces are striated and have a vitreous luster, while the top and bottom faces are smooth and have a pearly luster. The forms, then, are a pinacoid and square prism (tetragonal prism) instead of a cube. The apparent octahedron is in reality a double-ended square pyramid (tetragonal bipyramid in the language of crystallography.)

A more general method of determining the symmetry of a crystal is by means of etch-figures. When a crystal is acted upon by a solvent, the action is not uniform, but begins at certain points and proceeds more rapidly in some directions than in others. If the action is stopped at the right time, the faces of the crystal are usually found to be covered with little angular figures of definite shape and orientation called **etch-figures.** The etch-figures are usually shallow depressions bounded by minute faces, but in some cases they are elevations. The fact that these faces are often general forms (see p. 72) enables one in many cases to determine the crystal class. Without etching it would have been impossible to assign many crystalline substances to their proper crystal class. For example, the representatives of classes 9, 12, 23, and 24 (see p. 80,) were assigned to these classes, solely on account of the etch-figures and the assignment of many crystals, both minerals and prepared compounds, to their crystal class has been checked by the etch-figures. For example, the etch-figures on an etched prismatic crystal of nepheline is assigned to the hexagonal pyramidal class (A_6) solely on account of the etch-figures (Fig. 27).

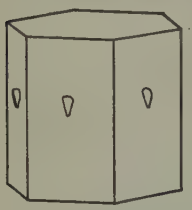


FIG. 27.—Etch-figures on nepheline crystal.

The shape of the etch-figures varies with the solvent, time, and temperature, but whatever their shape they are practically always the same in symmetry. On similar faces the etch-figures are alike and on dissimilar faces they are unlike, hence we have an exact method of determining the forms present on the crystal (see Fig. 28). The faces of etch-figures lie in well developed

zones, but they often have high indices. There is no rule to follow in obtaining etch-figures as it is simply a question of ease of solution. Crystals soluble in water may furnish them by passing a moistened cloth over the surface, while some refractory minerals such as topaz require fused potassium hydroxid.

Crystals are sometimes found with natural etch-figures. Diamond crystals, for example, very often have triangular etch-figures on the octahedral faces (see Fig. 378, p. 214).

Closely related to etch-figures there are often found growth-figures produced, not by solution, but by growth, and these may

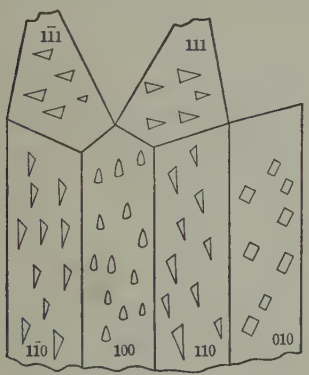


FIG. 28.—Etch-figures on diopside. (Modified from Ries.)

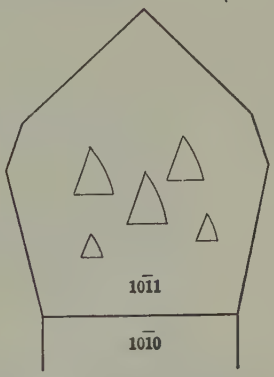


FIG. 29.—Growth-figures on quartz crystal.

indicate the symmetry of the crystal. On quartz, for example, these are sometimes found on the rhombohedral faces $r\{10\bar{1}1\}$ and $x\{01\bar{1}1\}$ as illustrated in Fig. 29.

Optical characters are also useful in determining the true symmetry of a crystal. For example, stilbite crystals (see Fig. 574, p. 409) are apparently rhombic bipyramidal, but optical examination of a thin-section parallel to the cleavage face *b* proves them to be monoclinic prismatic crystals twinned on the *c* face, *i.e.*, they are composite crystals made up of two individuals.

5. THE FORMS OF CRYSTALS

The similar faces of a crystal constitute a **form,** the word "form" being used here in a special technical sense. Similarity

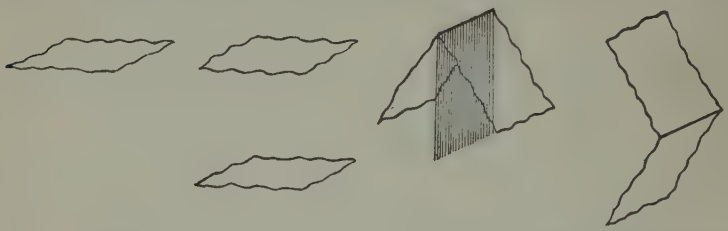


FIG. 30.—Pedion. FIG. 31.—Pinacoid. FIG. 32.—Dome. FIG. 33.—Sphenoid.

of faces on some crystals may be observed at a glance, but for others not only careful examination and measurement, but also

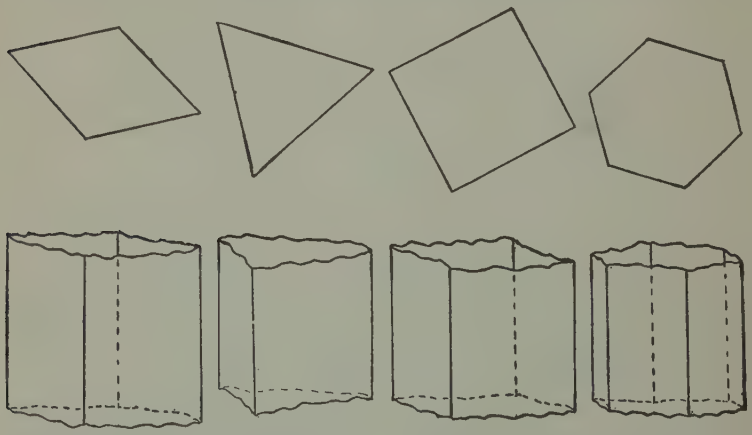


FIG. 34. Rhombic prism. FIG. 35. Trigonal prism. FIG. 36. Tetragonal prism. FIG. 37. Hexagonal prism.

etching with some solvent is necessary. Similar faces will have the same kind of etch-figures as has been mentioned in the preceding section.

There are many kinds of forms. The most logical method is to name the forms according to geometrical principles, regardless of their position with respect to axes of reference (see p. 73). A single face is called a **pedion** (Fig. 30). Two parallel faces constitute a **pinacoid** (from the Greek word for a board) (Fig. 31). A form composed of two non-parallel faces is known as a **dome** (from the Latin word for house) if astride a plane of symmetry (Fig. 32), but a **sphenoid**[1] (from the Greek word for wedge), if not astride a plane of symmetry (Fig. 33).

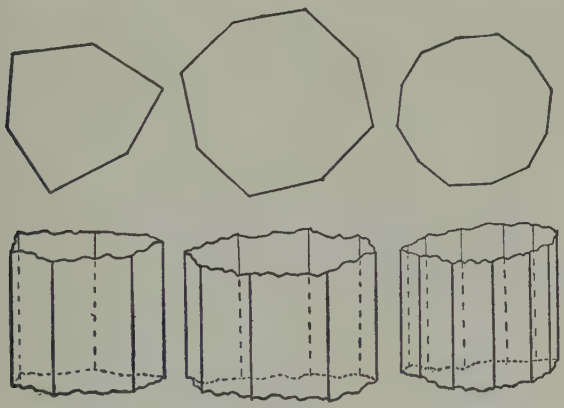


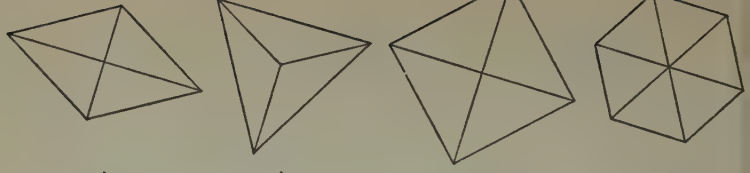
FIG. 38. Ditrigonal prism

FIG. 39. Ditetragonal prism.

FIG. 40. Dihexagonal prism.

Next we have three, four, six, eight, or twelve similar faces in one zone. These are called **prisms,** and are distinguished according to their cross-section as trigonal (Fig. 35), rhombic (Fig. 34), tetragonal (Fig. 36), hexagonal (Fig. 37), ditrigonal (Fig. 38), ditetragonal (Fig. 39), and dihexagonal (Fig. 40). **Pyramids** are forms consisting of three or more similar faces intersecting in a point. They are defined by the shape of the cross-section just as the prisms are. See Figs. 41 to 44, and 49 to 51. **Bipyramids**

[1] These two (dome and sphenoid) are known by different names because one results from reflection in a plane, and the other from revolution of 180° about an axis.



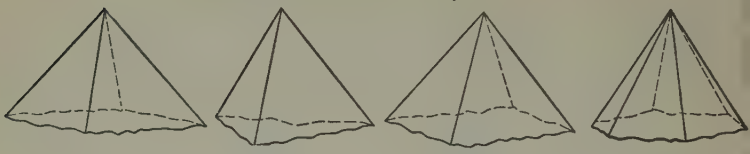


FIG. 41. FIG. 42. FIG. 43. FIG. 44.

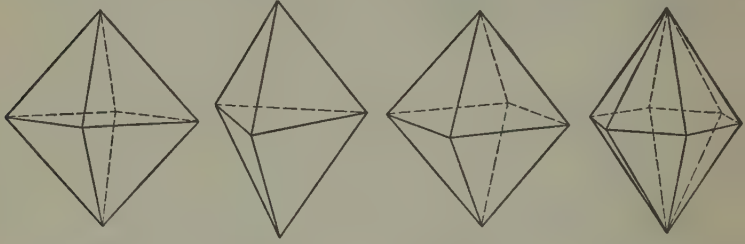


FIG. 45. Rhombic. FIG. 46. Trigonal. FIG. 47. Tetragonal. FIG. 48. Hexagonal.

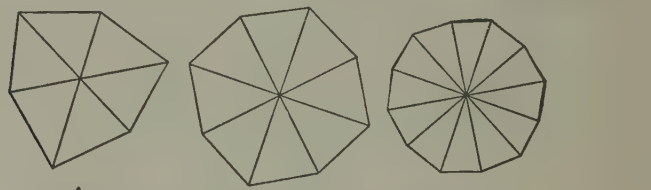


FIG. 49. FIG. 50. FIG. 51.

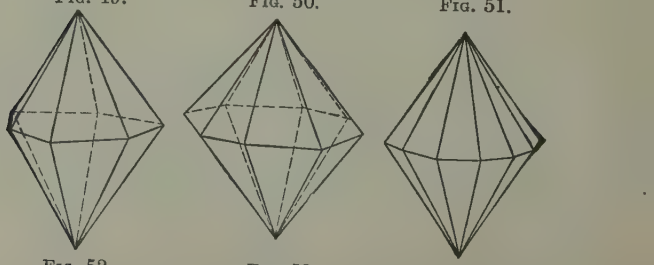


FIG. 52. Ditrigonal. FIG. 53. Ditetragonal. FIG. 54. Dihexagonal.

FIGS. 41–54.—Pyramids and bipyramids.

are double-ended forms which may be imagined to be formed by placing two pyramids end to end. They are defined by cross-section just as prisms and pyramids are. See Figs. 45 to 48 and 52 to 54.

FIG. 55.

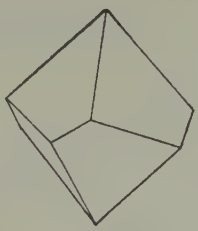


FIG. 56.

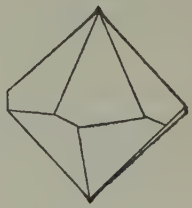


FIG. 57.

Trigonal trapezohedron. Tetragonal trapezohedron. Hexagonal trapezohedron.

Trapezohedrons are double-ended forms with the symmetry $\mathbf{A_n \cdot nA_2}$. They are distinguished as trigonal (Fig. 55), tetragonal (Fig. 56), or hexagonal (Fig. 57), according to the period n of the axis $\mathbf{A_n}$. **Bisphenoids** are forms consisting apparently of two sphenoids placed together symmetrically. They are called rhombic (Fig. 62), or tetragonal (Fig. 16), according to cross-section. A **rhombohedron** is a form consisting of six rhombic faces, three at each end of a six-fold axis of composite symmetry (Fig. 17). It is like a cube symmetrically distorted along one of its diagonals. **Scalenohedrons** are double-ended forms consisting of scalene triangular faces meeting in zigzag lateral edges. They are distinguished by their cross-section as tetragonal (Fig. 58) or hexagonal (Fig. 59).

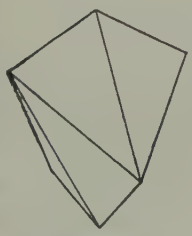


FIG. 58. Tetragonal scalenohedron.

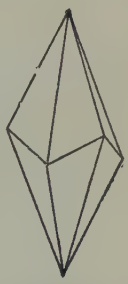


FIG. 59. Hexagonal scalenohedron.

There are fifteen more kinds of forms which are restricted to the isometric system. Some of these, such as cube, octahedron, and tetrahedron are simple, but as most of them are rather

complicated, their description is deferred until the isometric system is studied.

Of the forty-eight kinds of forms possible, all but four have been found on crystals. The four are the tetragonal trapezohedron, the ditetragonal pyramid, the hexagonal trapezohedron, and the dihexagonal pyramid. They are possible forms because they each have the symmetry of one of the 32 crystal classes. See table on p. 80.

The thirty-two forms which result from the symmetry operations performed on a given face are **general forms.** The other sixteen forms result when the face occupies a special position

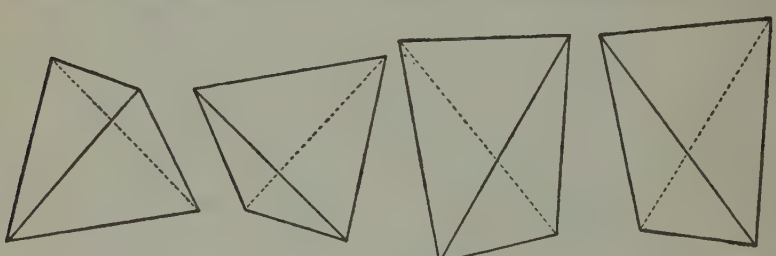


FIG. 60. FIG. 61. FIG. 62. FIG. 63.
Congruent tetrahedra. Enantiomorphous rhombic bisphenoids

with respect to the elements of symmetry. Thus a hexagonal prism results in class 23 when a face is parallel to the A_6.

Of the above mentioned forms, the pyramids, prisms, pinacoid, dome, sphenoid, and pedion cannot occur by themselves; and for that reason are called **open forms.** All the others are called **closed forms** because by themselves they enclose space.

Two forms are said to be **congruent** if one of them may be made coincident with the other by rotation. For example, the tetrahedra of Figs. 60 and 61 are congruent. Two forms are said to be **enantiomorphous** if they are non-superposable and the mirror-image of each other. (The right hand and the left hand, for example, are enantiomorphs). Thus the rhombic bisphenoids of Figs. 62 and 63 are enantiomorphous. Two forms are said to be **complementary** when their combination is *geometrically* indis-

tinguishable from another kind of form. For example, the two tetrahedra of Fig. 25 are complementary, for geometrically they form an octahedron.

Another method of naming forms used by some crystallographers is based upon the position of faces with respect to the axes of reference (see below). Thus a *pinacoid* is defined as a form that cuts one axis and is parallel to the other two. A *prism* is defined as a form that is parallel to the vertical axis and cuts the other two. A form that is parallel to one of the lateral axes and cuts the other two is a *dome*. A form that cuts all three axes is in general called a *pyramid*. A pyramid developed at only one end of the verticle axis is known as a *hemimorphic pyramid*. In the monoclinic and triclinic systems the names of forms are based upon the analogy of these systems with that of the orthorhombic. For example, in the monoclinic system $\{hkl\}$ is called a *hemi-pyramid* because there are one-half as many faces as in the corresponding form of the orthorhombic system; while $\{hkl\}$ in the triclinic system is a *tetarto-pyramid*, as there are two faces instead of eight. In the monoclinic system $\{h0l\}$ is a *hemi-dome* because $\{h0l\}$ in the orthorhombic system is a dome. In the triclinic system $\{hk0\}$ is a *hemi-prism* consisting of two opposite parallel faces instead of the four faces of the prism $\{hk0\}$ of the orthorhombic system. But, as was said before, the logical names of forms are based upon their symmetry and shape, and not upon their position with respect to the axes of reference.

6. THE NOTATION OF CRYSTAL FACES

Crystal measurement proves that exact mathematical relations exist between crystal faces. To make use of this fact the position of crystal faces is defined by the method of analytic geometry, which consists in referring them to three (in one case, four) suitably chosen coördinate axes passing through the center of the crystal. These axes are sometimes called crystallographic axes, but they should be called **axes of reference** to distinguish them from axes of symmetry. The selection of these axes is more or less arbitrary, but they are chosen so as to yield the simplest relations possible. Therefore they are usually either axes of symmetry, normals to planes of symmetry, or lines parallel to prominent edges.

Any face may be defined by its intercepts on the axes of reference which in the most general case intersect at oblique angles. In Fig. 64 the axes are the dot-and-dash lines OX, OY, and OZ

intersecting at the origin, O. The intercepts of the plane ABC (extension of the face *m*) are OA, OB, and OC. The intercepts of the plane HKL (extension of the face *n*) are OH, OK, and OL. Now it has been found that the ratios OA: OH, OB: OK, and OC:OL on any one crystal are practically always *simple rational numbers* such as 1:3, 1:2, 1:1, 3:2, 2:1, 4:1, etc. This, the second fundamental law of geometrical crystallography, is known as the **law of rational indices** (Haüy, 1784). The ratios OA: OB: OC and OH: OK: OL are, on the other hand, in general irrational.[1] In Fig. 64 the ratios OA: OH = 1:2, OB: OK = 1:1, OC: OL = 3:2.

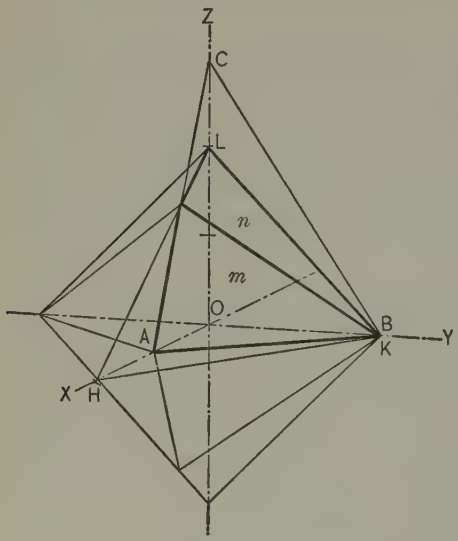


FIG. 64.

In the case of the mineral barite, the relative intercepts of some of the faces are as follows (the letters refer to Fig. 65).

Face	*Relative intercepts*	*Weiss symbols*	*Miller symbols*
m	0.815: 1: ∞	$\breve{a}$: $\bar{b}$: ∞$\dot{c}$	110
a	0.815: ∞ : ∞	$\breve{a}$: ∞$\bar{b}$: ∞$\dot{c}$	100
u	0.815: ∞ :1.313	$\breve{a}$: ∞$\bar{b}$: $\dot{c}$	101
d	0.815: ∞ :0.656	$\breve{a}$: ∞$\bar{b}$: ½$\dot{c}$	102
l	0.815: ∞ :0.328	$\breve{a}$: ∞$\bar{b}$: ¼$\dot{c}$	104
c	∞ : ∞ :1.313	∞$\breve{a}$: ∞$\bar{b}$: $\dot{c}$	001
o	∞ : 1:1.313	∞$\breve{a}$: $\bar{b}$: $\dot{c}$	011
y	0.815:0.5:0.656	$\breve{a}$: ½$\bar{b}$: ½$\dot{c}$	122
z	0.815: 1:1.313	$\breve{a}$: $\bar{b}$: $\dot{c}$	111

[1] On isometric crystals even these ratios are rational and on tetragonal and hexagonal crystals two of the three ratios are rational. This fact is expressed as the **law of rational symmetric intercepts** (Friedel, 1905).

As the expressions for the intercepts are cumbersome, a very simple method of notation is suggested by the fact that these values for different faces are in the ratio of sample rational numbers (or infinity). We may select the expression for one of these faces as a standard, and represent the other faces by the numbers or infinity. In barite the face *z* with the intercepts 0.815: 1:1.313 has been taken as the **unit face.** This establishes the **axial ratio** as $\breve{a}:\breve{b}:\breve{c} = 0.815:\ 1:1.313$.

The symbols for the other faces may be written as in the third column. These are called **Weiss symbols** from the name of the German crystallographer who proposed this method (1818). The general expression for a face in this method of notation is $na:pb:mc$, where n, p, and m are simple numbers or fractions, or infinity and are called **coefficients.**

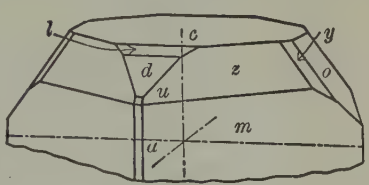


FIG. 65.—Barite crystal.

As the order *a*, *b*, *c* is always understood, these letters may be omitted and as infinity is inconvenient in mathematical calculations, the reciprocal values of the ratios may be used. We then have the symbols of the fourth column. If OA:OB:OC are the intercepts of a unit face, the symbol of another face with the intercepts OH:OK:OL is *hkl* in the expression $\mathrm{OH}:\mathrm{OK}:\mathrm{OL} = \frac{OA}{h}:\frac{OB}{k}:\frac{OC}{l} = \frac{a}{h}:\frac{b}{k}:\frac{c}{l}$. The three simplest whole numbers *h*, *k*, *l*, that express this ratio are called the **Miller indices,** as Miller, formerly professor of mineralogy at the University of Cambridge, was the first to make extensive use of this method. The Miller symbol *hkl* is a kind of algebraic expression standing for certain numbers and so is called a **type symbol.** Besides a face *hkl* that cuts all three axes of reference, we have the faces *hk*0, *h*0*l*, and 0*kl*, each of which intersects two axes and is parallel to the third and *h*00 (100), 0*k*0(010), and 00*l*(001) each of which intersects one axis

and is parallel to the other two. These constitute the seven so-called type symbols. They are represented in Fig. 66. Figure 67 represents an olivine crystal with seven actual type forms $a\{100\}$, $b\{010\}$, $c\{001\}$, $m\{110\}$, $d\{101\}$, $k\{021\}$, $p\{111\}$. As in analytic geometry, the front, right, and top ends of the axes are considered as positive, while the back, left, and bottom ends are considered as negative. A negative index is indicated by a line over the letter. There are eight planes which cut the axes at the same relative distances, but in different octants. They are hkl, $\bar{h}kl$, $\bar{h}\bar{k}l$, $h\bar{k}l$, $hk\bar{l}$, $\bar{h}k\bar{l}$, $\bar{h}\bar{k}\bar{l}$, and $h\bar{k}\bar{l}$. These symbols as just written

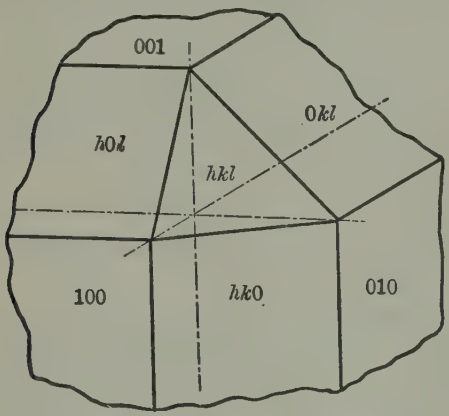


Fig. 66.—The seven type faces.

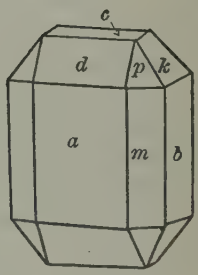


Fig. 67.—Olivine crystal.

are **face-symbols,** but the symbol of one face hkl may be taken to represent the form. The **form-symbol** is usually written with brackets $\{hkl\}$ to distinguish it from a face-symbol hkl or (hkl). In order to determine the type symbol it is only necessary to write the indices h, k, l, in the order of the axes a, b, c, and to substitute 0 if the face is parallel to an axis. In writing type symbols the reciprocal idea may be disregarded except for the zero.

The determination of the symbol involves calculation by means of trigonometry, or the corresponding graphic solution. A

simple case is illustrated by Fig. 68, which represents the vertical prism zone of cerussite. Here we have a rectangular zone of (hk0) faces, a, m, r, b, where a is (100) and b is (010), (the axes of reference are parallel to these two faces). Assuming m to be (110), the problem is to determine the symbol of r. Move r parallel to itself until r' and m intersect the a-axis at a common point. Then the intercept of r' on the b-axis, it may be seen, is one-third of that of m. The intercepts of the r-face are $1\breve{a}$: $\frac{1}{3}\bar{b}$: $\infty\dot{c}$ or $\frac{1}{1}\breve{a}$: $\frac{1}{3}\bar{b}$: $\frac{1}{\infty}\dot{c}$. The Miller indices are (130) (read one, three, zero).

The law of the rationality of the indices, which has been established by the measurement of thousands of crystals, is the foundation of geometrical crystallography. After the axial ratio for a given substance has once been established by a unit face, all the other possible faces may be predicted, for their interfacial angles can be calculated by the formulæ of plane or spherical trigonometry.

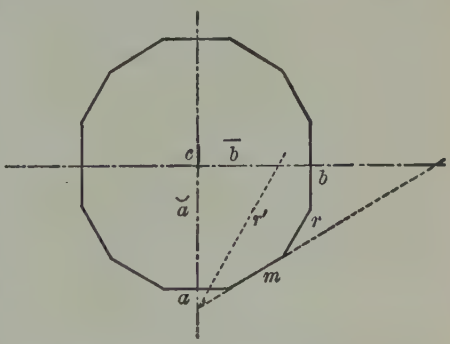


FIG. 68.—Graphic determination of indices.

Why the symbol (111), in the case of barite for example, does not represent a face that cuts the three axes at equal lengths is one of the most difficult points for the student of crystallography to comprehend. Several illustrations may clear up this point. Imagine two cities laid out according to different plans. In one, the blocks are 475 feet long and 325 feet wide, and in the other 650 feet long and 300 feet wide. A pedestrian on inquiring about a certain building in either place might be directed to go two blocks north and three blocks east. Yet the actual distance for him to walk in the two cities would be different, for the lengths of the blocks are different. Altho the lengths of the blocks are on

record in the city engineer's office, the pedestrian is not directly concerned with them, but only with the directions given him. The axial ratios for crystals are established and on record in reference books, but in the description of the various crystal faces and forms, use is always made of Miller indices or other symbols rather than of the intercepts of the faces.

Another analogous case that will appeal to the student of chemistry is the law of definite proportions and the law of multiple proportions. In the chemical formulæ, CuO and Cu_2O, CuO means that there are 63.6 parts (by weight) of copper and 16 parts of oxygen, while Cu_2O means that there are 127.2 (2×63.6) parts of copper and 16 parts of oxygen. The atomic weights have been determined and are given in tables, but they are not expressed in chemical formulæ.

In order that the symbols may be as simple as possible, it has been found convenient to have six kinds of sets of axes of reference; crystals of every known substance may be referred to some one of these sets. The axes of reference differ in their inclinations to each other and the unit lengths on the axes also differ in their relative length. For crystals with a single axis of 3-fold symmetry or 6-fold symmetry it is more convenient to use four axes of reference (see p. 102).

7. THE CLASSIFICATION OF CRYSTALS

The Crystal Classes. The modern classification of crystals is based upon symmetry. Only axes of 2-fold, 3-fold, 4-fold, and 6-fold symmetry have ever been found on crystals. With this limitation it may be proved mathematically that only thirty-one combinations of symmetry elements are possible. These thirty-one divisions together with the one division devoid of symmetry constitute the **thirty-two crystal classes.** Examples of all of these but one (A_3.P) have been found either among minerals, or compounds made in the laboratory. It is interesting to note that just as Mendeléef, the Russian chemist, predicted the exist-

ence and even the properties of several chemical elements by the discovery of the periodic law, so Hessel, a German mineralogist, in 1830 predicted the thirty-two possible crystal classes when representatives of only about half of them were known.

The table on page 80 gives the name of the class, the number of faces in the general form, the symmetry, and a typical example. The name of the form with the symbol $\{hkl\}$ ($hk\bar{i}l$ in the hexagonal system), or the **general form** as it is called, gives the name to the class. In contradistinction, the other forms are called **limit forms.** This term may be explained by considering a pyramidal face (hkl) in the rhombic bipyramidal class. By increasing its intercept on the vertical axis it becomes steeper and steeper, its limit in this case being the prism ($hk0$). By decreasing its intercept on the vertical axis it becomes less steep, its limit in this case being the pinacoid (001). If its intercept on the b-axis is increased it gradually passes into $\{hol\}$, another limit form, while if its intercept on this axis is decreased it becomes $\{010\}$. Similarly by increasing its intercept on the a-axis it passes into its limit ($0kl$) and then by decreasing its intercept it becomes (100).

The forms corresponding to the type symbols in any class may be found from the symmetry by a graphical method. Indicate a- and b-axes by two dot-and-dash lines at right angles (oblique angles in the triclinic system). Their intersection is the projection of the c-axis. Then indicate the symmetry elements in their proper positions by the following conventions: A full line represents a plane of symmetry. A plane of symmetry parallel to the plane of the paper may be indicated by a heavy circle of convenient diameter. Denote axes of 2-, 3-, 4-, and 6- fold symmetry by small ellipses, triangles, squares, and hexagons, respectively. As an example, let it be required to find the forms represented by the type symbols of the rhombic pyramidal class with the symmetry, $A_2 \cdot 2P$. In Fig. 69 the two planes of symmetry are represented by two full lines which coincide with the projection of the axes of reference a and b. Their intersection is the axis of 2-fold symmetry. Projections of the faces in the upper octants are small crosses. (For faces in the lower octants circlets may be used.) Faces parallel to the vertical axis may be indicated by arrows. The general form of this class is a rhombic pyramid, for the symmetry requires (hkl), ($\bar{h}kl$), and ($h\bar{k}l$) to accompany

Table of the Thirty-two Crystal Classes

System	No.	Name of Class	Faces in general form	Symmetry	Example[1]
Triclinic	1	Asymmetric	1	No symmetry.	$(CaS_2O_3 \cdot 6H_2O)$
	2	Pinacoidal	2	C	Albite
Monoclinic	3	Sphenoidal	2	A_2	(Sucrose [sugar])
	4	Domatic	2	P	Clinohedrite
	5	Prismatic	4	$A_2 \cdot P \cdot C$	Gypsum
Orthorhombic	6	Rhombic bisphenoidal	4	$3A_2$	Epsomite
	7	Rhombic pyramidal	4	$A_2 \cdot 2P$	Calamine
	8	Rhombic bipyramidal	8	$3A_2 \cdot 3P \cdot C$	Barite
Tetragonal	9	Tetragonal bisphenoidal	4	$A_2(\not{P}_4)$	$(Ca_2Al_2SiO_7)$
	10	Tetragonal pyramidal	4	A_4	$[Ba(SbO)_2(C_4H_4O_6) \cdot 2H_2O)]$
	11	Tetragonal scalenohedral	8	$A_2(\not{P}_4) \cdot 2A_2 \cdot 2P$	Chalcopyrite
	12	Tetragonal trapezohedral	8	$A_4 \cdot 4A_2$	$(NiSO_4 \cdot 6H_2O)$
	13	Tetragonal bipyramidal	8	$A_4 \cdot P \cdot C$	Scheelite
	14	Ditetragonal pyramidal	8	$A_4 \cdot 4P$	$(AgF \cdot H_2O)$
	15	Ditetragonal bipyramidal	16	$A_4 \cdot 4A \cdot 5P \cdot C$	Zircon
Hexagonal	16	Trigonal pyramidal	3	A_3	$(NaIO_4 \cdot 3H_2O)$
	17	Rhombohedral	6	$A_3(\not{P}_6)C$	Phenacite
	18	Trigonal trapezohedral	6	$A_3 \cdot 3A_2$	α-Quartz
	19	Ditrigonal pyramidal	6	$A_3 \cdot 3P$	Tourmaline
	20	Hexagonal scalenohedral	12	$A_3(\not{P}_6) \cdot 3A_2 \cdot 3P \cdot C$	Calcite
	21	Trigonal bipyramidal	6	$A_3 \cdot P$	———
	22	Ditrigonal bipyramidal	12	$A_3 \cdot 3A_2 \cdot 4P$	Benitoite
	23	Hexagonal pyramidal	6	A_6	Nepheline
	24	Hexagonal trapezohedral	12	$A_6 \cdot 6A_2$	β-Quartz
	25	Hexagonal bipyramidal	12	$A_6 \cdot P \cdot C$	Apatite
	26	Dihexagonal pyramidal	12	$A_6 \cdot 6P$	Iodyrite
	27	Dihexagonal bipyramidal	24	$A_6 \cdot 6A_2 \cdot 7P \cdot C$	Beryl
Isometric	28	Tetartoidal	12	$4A_3 \cdot 3A_2$	Ullmannite
	29	Gyroidal	24	$3A_4 \cdot 4A_3 \cdot 6A_2$	Sylvite
	30	Diploidal	24	$4A_3(4\not{P}_6) \cdot 3A_2 \cdot 3P \cdot C$	Pyrite
	31	Hextetrahedral	24	$4A_3 \cdot 3A_2(3\not{P}_4) \cdot 6P$	Tetrahedrite
	32	Hexoctahedral	48	$3A_4 \cdot 4A_3(4\not{P}_6) \cdot 6A_2 \cdot 9P \cdot C$	Galena

(hkl). For a face $(0kl)$, the symmetry requires $(0\bar{k}l)$; the form $\{0kl\}$, then, is a dome. Similarly $\{h0l\}$ is a dome; $\{hk0\}$ is a rhombic prism; $\{100\}$ and $\{010\}$ are each pinacoids, while $\{001\}$ is a pedion consisting of a single face. In the lower half of the crystal $\{hk\bar{l}\}$ is a rhombic pyramid; $\{0k\bar{l}\}$, and $\{h0\bar{l}\}$, domes; while $\{00\bar{1}\}$ is a pedion. The forms on the lower half of the crystal in this case are independent of those on the upper half. Calamine, an example of a crystal belonging to the rhombic pyramidal class, is shown in Fig. 70. Here the forms are $c\{001\}$, $t\{301\}$, $i\{031\}$, $b\{010\}$, $m\{110\}$, and $v\{12\bar{1}\}$.

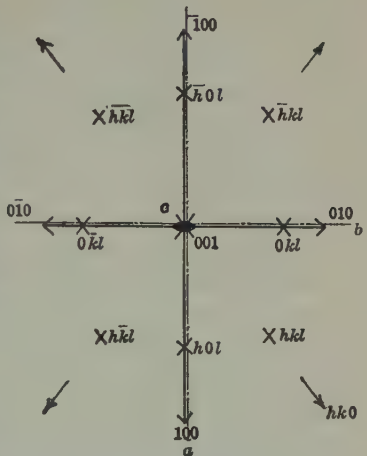


FIG. 69.—Graphic method of determining the possible forms in a crystal class.

The Crystal Systems. Although the thirty-two classes are fundamental in the classification of crystals, it is convenient to assemble them in larger groups called **crystal systems**. Six crystal systems are generally recognized. It is not always possible to determine the crystal class by inspection, but the crystal system is usually apparent in well-formed crystals. If **directions fixed by symmetry** (either axes of symmetry or lines normal to planes of symmetry) are chosen for axes of reference it is found that all equivalent faces are represented by indices which differ from each other only in their order of succession and sign. If this be done, one symbol (enclosed in brackets) may stand for all the faces of a form.

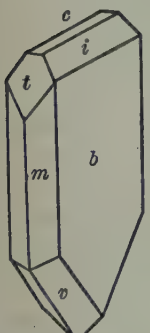


FIG. 70.—Calamine.

The classification of crystals into systems is largely one of convenience to bring out the relation of crystal form to physical properties, but for all practical purposes in elementary work it may be said to rest upon the character of the axes of reference fixed by sym-

metry. Accordingly the following six systems are recognized: Isometric, tetragonal, hexagonal, orthorhombic, monoclinic, and triclinic.

Crystals with three like or interchangeable directions of symmetry at right angles to each other are referred to the **isometric system.** These three directions, which are either 2-fold or 4-fold axes of symmetry, constitute the axes of reference for this system.

Crystals with a single 4-fold axis (or a single composite 4-fold axis, $\not P_4$) are referred to the **tetragonal system.** The other two axes of reference, which may, or may not, be directions fixed by symmetry, are interchangeable and are at right angles to each other and also at right angles to the principal axis.

Crystals with a single 3-fold or 6-fold axis of symmetry (including $\not P_6$) are referred to the **hexagonal system.** Four axes of reference are usually employed, one (A_3 or A_6) at right angles to three interchangeable ones which are in one plane and intersect each other at angles of 120°. The three lateral axes of reference may or may not be directions of symmetry.

Crystals with three unlike or non-interchangeable directions of symmetry at right angles and no other directions of symmetry are referred to the **orthorhombic system.** These three directions are the axes of reference.

Crystals with a single direction fixed by symmetry, not previously included, are referred to the **monoclinic system.** This direction is an axis of reference; the other two are in a plane normal to it but are in general oblique to each other.

Crystals without any directions fixed by symmetry are referred to the **triclinic system.** There are three non-interchangeable axes of reference, in general at oblique angles to each other.

In the case of each of the six systems, at least some of the directions fixed by symmetry are used for axes of reference. If there are not enough axes of reference, then lines parallel to prominent edges or perpendicular to prominent faces are chosen.

The forms of the crystal class with the highest grade of symmetry in each system are sometimes called **holohedral** or whole forms, while many of the forms of the classes of lower grade of symmetry are called **hemihedral** or half forms, because they have half the number of faces of the holohedral forms. There is a geometrical resemblance between these two kinds of forms. A tetrahedron, for example, is said to be the hemihedral form of an octahedron, for it may be derived by extending alternate faces and suppressing the others as shown in Fig. 71. A cube has no hemihedral form, or rather the hemihedral and holohedral cubes are geometrically identical, for the supression of alternate octants still leaves the cube. The same is true of the rhombic dodecahedron.

The symmetrical suppression of the faces of the general forms of the six holohedral classes gives rise to twenty-six divisions. These, together with the six holohedral divisions, lead to the thirty-two classes before mentioned. The general forms of the five isometric classes may be derived from the hexoctahedron thus: The suppression of faces of alternate octants gives the hextetrahedron, the suppression of alternate faces gives the gyroid, the suppression of faces in pairs astride the planes of symmetry gives the diploid, while the combination of any two of these methods gives a twelve-sided figure called the tetartoid. As this form has one-fourth the number of faces of the hexoctahedron, it is called a **tetartohedral** or quarter form.

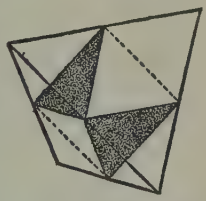


FIG. 71.—The derivation of the tetrahedron from the octahedron.

The idea of hemihedrism implies that the six crystal systems are fundamental, whereas we know that the crystal classes are more fundamental. Hence the terms involving hemihedrism are now of historical interest only. The class with the highest symmetry in each system may be called **holosymmetric** instead of holohedral.

8. CRYSTAL DRAWING

Before the crystal systems and classes are described in detail the method of drawing crystals will be explained.

Crystal drawings are parallel projections made by drawing parallel lines from the vertices of the crystal to the plane of projection. If the projectors are perpendicular to the plane of projection, we have an orthographic projection; if the projectors are inclined to the plane of projection, we have a clinographic projection.

The **orthographic projection** is especially useful in the graphic determination of the indices of crystal faces and axial elements. An orthographic projection is easily made from the interfacial angles, without any knowledge of the axial ratios, simply by dropping perpendiculars from the vertices of the crystal to the plane of projection which is usually an actual or possible crystal face. All faces normal to the plane of the drawing appear as lines inclined to each other at their true angles. Horizontal edges of the crystal appear in their true length, but oblique edges are foreshortened. Orthographic projections lack the appearance of solidity given by clinographic projections, but by combining two orthographic projections made on planes at right angles to each other, a plan and elevation are obtained, which together give a good idea of the crystal habit. Fig. 72 is a plan and front elevation of a topaz crystal with the forms $c\{001\}$, $y\{041\}$, $m\{110\}$, $l\{120\}$, $u\{111\}$, and $i\{223\}$. The plan[1] (top figure) was constructed by laying off the interfacial angles mm, ml, and ll and by placing i and u in the same zone with c and m. The elevation (lower figure) was constructed from the interfacial angle cy and by observing zonal relations. The fact that corresponding points in the plan and elevation lie on the same vertical line greatly facilitates the construction. For example, the directions of the intersection edge ul in the elevation and iy in the plan are determined automatically, provided a supplementary elevation is made.

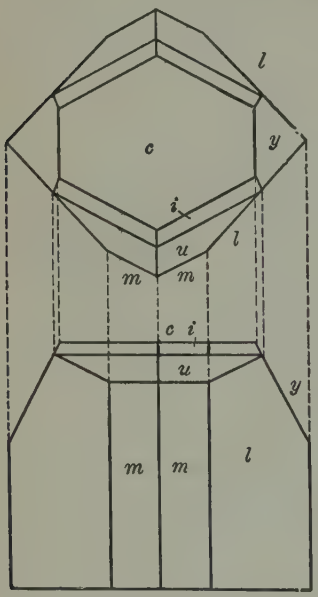


FIG. 72.—Plan and elevation of topaz crystal.

[1] The third angle projection is used.

From one or two orthographic projections of a crystal it is possible to derive graphically the Miller indices of the faces and the geometrical constants (axial ratio and axial angles). Examples will be shown under each crystal system. (See pages 97, 101, 111, 115, 120 and 123.) The orthographic projection may be used for graphic determinations but for general descriptive purposes (text-books and articles) clinographic projections are preferable, for they give the appearance of solidity.

The **clinographic parallel projection** or so-called parallel perspective is used instead of a true perspective because the parallelism of edges or the occurrence of crystal faces in zones is one of the prominent features of crystals and should be retained in the drawing. The clinographic projection is made on a vertical plane by inclined projectors taken so that one sees both the top and the right side of the crystal.

The first step in producing a clinographic projection of a crystal is to make an isometric **axial cross.** The method of making an isometric axial cross is shown in Fig. 73. The upper right-hand part (*a*) of the figure shows the rotation of the plan of the axial cross 18° 26′ to the left. (This angle is chosen because its tangent is $\frac{1}{3}$). The left-hand portion of the figure (*b*) shows the projection of an elevation of the axial cross by projectors inclined 9° 28′ (taken because its tangent is $\frac{1}{6}$) from the horizontal on a vertical plane. The lower right-hand part of the figure (*c*) shows the method of obtaining the axial cross (dot-and-dash lines). The *OC*-axis is given in its full length, but both the *OA*-axis and the *OB*-axis are foreshortened.

The isometric axial cross is modified for the other systems. In the tetragonal system the unit length on the vertical axis is either greater or less than that on the lateral axes. The unit lengths of the axial cross of a vesuvianite, for example, are: $OA : OB : 0.537 \times OC$. In the hexagonal system there are three lateral axes. The method of determining these lateral axes is shown in Fig. 74. The line *OS* is made equal to $1.732 \times OA$ (Fig. 73), and *S* is joined with *B* and *B′*. *BS* and *B′S* are bisected

at the points Q and R. ROR', QOQ', and BOB' are the unit lengths of the three lateral axes. The unit length on the vertical axis is modified according to the value on record. In the orthorhombic system both the unit lengths on the OA-axis and OC-axis

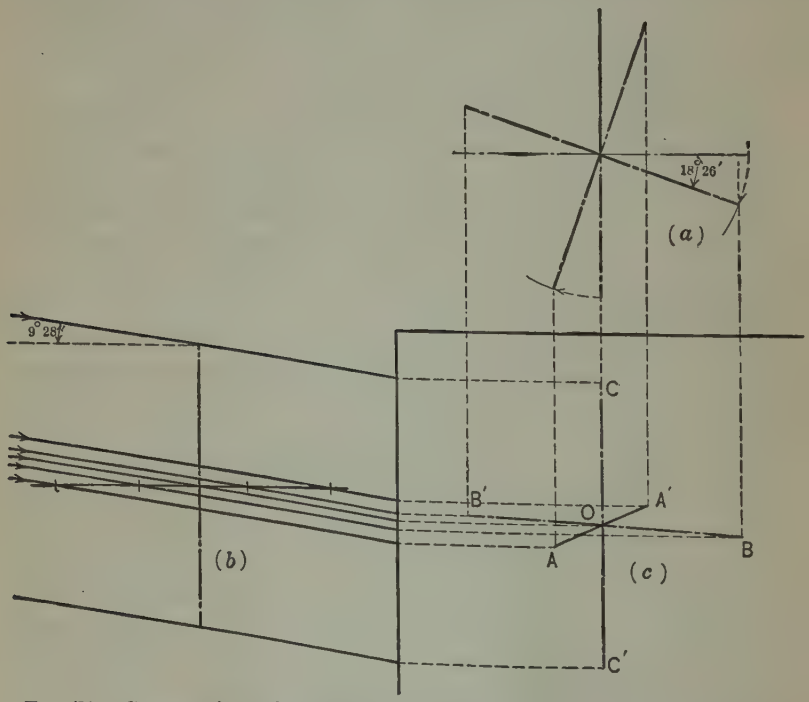


FIG. 73.—Construction of isometric axial cross in clinographic projection (modified from French).

are modified. For example, the three values for barite are $0.815 \times OA : OB : 1.313 \times OC$.

In the monoclinic and triclinic systems the angles between the axes are also modified. For the angle β between a and c the position of the a-axis is changed as follows: On the axis OC (Fig. 75) the distance $OM = \cos \beta \times OC$ is laid off and on the axis OA

the distance $ON = \sin \beta \times OA$ is laid off. Then the b-axis is the line QOQ', QO being the diagonal of a parallelogram $MQNO$. The lengths of the axes are modified as in the other systems.

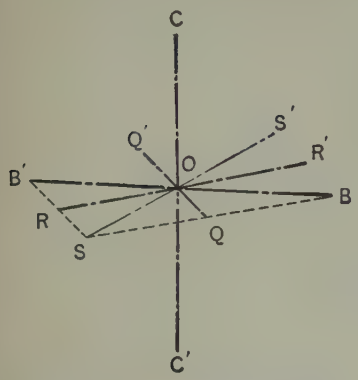


FIG. 74.—Hexagonal axial cross.

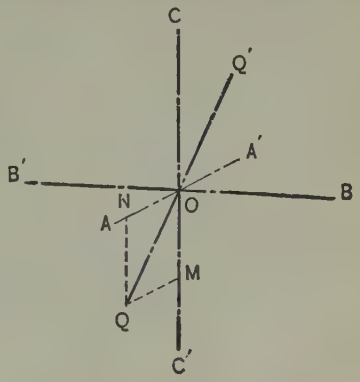


FIG. 75.—Monoclinic axial cross.

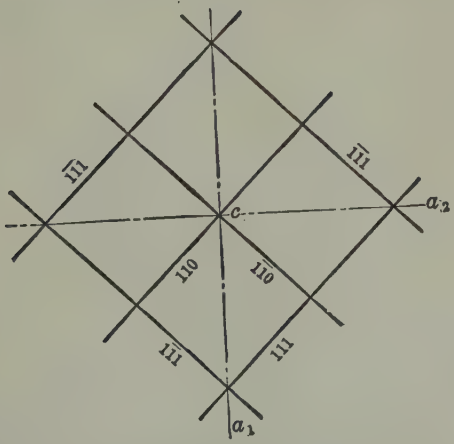


FIG. 76.—Linear projection of a scapolite crystal.

After the axes are projected in their proper positions, crystals consisting of a single form are drawn by finding the intersection

of the faces on the axial cross and connecting them with lines. For crystals with two or more forms, use is made of the **linear projection.** In the linear projection each face is represented by a line. The lines are the intersections of faces, shifted parallel to themselves so that they cut the vertical axis (c) at unity, with

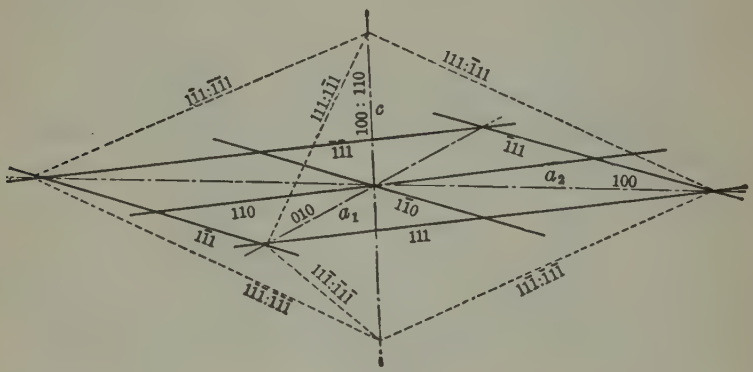


FIG. 77.

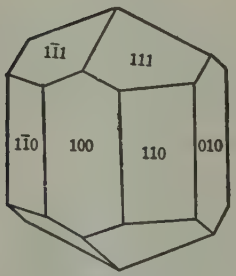


FIG. 78.

FIGS. 77–78.—Clinographic projection of a scapolite crystal.

the plane of projection which is a plane through the center of the crystal, perpendicular to the c-axis. Figure 76 shows a linear projection of the scapolite crystal of Fig. 78. It is necessary to plot a linear projection of the crystal on these axes by taking the reciprocal of the Miller indices and then making the third term

equal to unity. The desired direction of the intersection edge of the two faces is a line joining the intersection of the linear projection of the two faces with the extremity of the vertical axis. Figure 77 shows the method of construction of the clinographic drawing of the scapolite crystal of Fig. 78. The dot-and-dash lines are the axes of reference; the heavy lines, the linear projection constructed on the axial cross; while the dotted lines are the directions of the intersection edges. The direction intersection of faces like (111) and (110), which do not intersect, is simply the direction of the lines.

9. ISOMETRIC SYSTEM

The isometric systems includes all crystals with three interchangeable axes of reference at right angles. All crystals of this system have four axes of 3-fold symmetry; many of them also have three axes of 4-fold symmetry.

The axes of reference are designated as in Fig. 79 with a_1, running front and back, a_2, running right and left, and a_3 in a vertical position. As all isometric crystals have identical angles for corresponding forms, there are no axial elements to be determined.

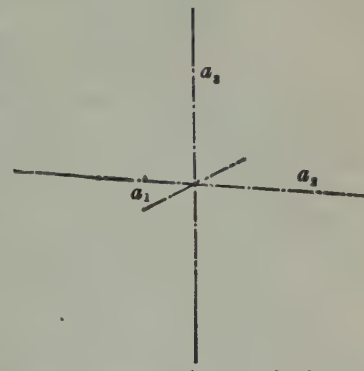


FIG. 79.—Isometric axes of reference.

There are five classes in the isometric system (see p. 80) but of these only the three that are of much practical importance will be discussed.

Isometric crystals, unless much distorted, are of about equal dimensions in all directions and this fact aids in their identification. Highly modified crystals may approach a sphere in general appearance.

Hexoctahedral Class. $3A_4 \cdot 4A_3(4P_6) \cdot 6A_2 \cdot 9P \cdot C$

(Holohedral)

The crystals of this class have the maximum degree of symmetry possible in crystals. The 4-fold axes are mutually perpendicular and lie at the intersections of three of the planes of symmetry (axial planes). The other six planes of symmetry (diagonal planes) intersect in the four axes of 3-fold symmetry. The 4-fold axes of symmetry are the axes of reference.

List of Forms in the Hexoctahedral Class

Cube	6 faces	{100}
Octahedron	8 faces	{111}
Dodecahedron	12 faces	{110}
Tetrahexahedron	24 faces	{hk0}
Trisoctahedron	24 faces	{hhl}
Trapezohedron	24 faces	{hkk}
Hexoctahedron	48 faces	{hkl}

[In the above symbols $h>k>l$]

Cube {100}. The cube (or hexahedron) is a six-faced form with interfacial angles of 90°. The ideal form is shown in Fig. 80. The cube is a common form on galena, fluorite, cuprite, and halite.

Octahedron {111}. As its name implies, this is an eight-faced form. Each face is an equilateral triangle in the ideal form.

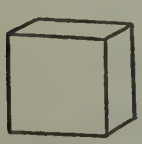


FIG. 80. {100}.

FIG. 81. {111}.

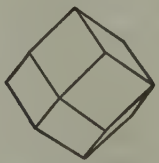


FIG. 82. {110}.

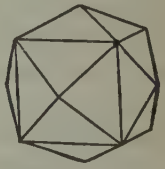


FIG. 83. {*hk*0}.

The interfacial angles are 70° 32′. (Fig. 81.) It is a common form on magnetite, spinel, and diamond.

Dodecahedron {110}. This form (Fig. 82) consists of twelve faces, each rhombic in shape. It is often called the rhombic dodecahedron to distinguish it from the regular dodecahedron of

geometry, which is a crystallographically impossible form. The interfacial angles are 60° and 90°. It is especially common on garnet.

Tetrahexahedron {hk0}. This form is so called because it apparently consists of a four-faced pyramid on each cube face. Figure 83 represents the form {210}. It is occasionally found on fluorite.

Trapezohedron {hkk}. Each face is a trapezoid. This form is sometimes called the tetragonal trisoctahedron to distinguish it from the next mentioned form, the trigonal trisoctahedron. Figure 84 represents the form {211} which is common on garnet, leucite, and analcite.

Trisoctahedron {hhl}. Each face is an isosceles triangle. With this form the intercept on the third axis is *greater* than the

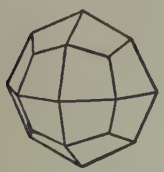


FIG. 84. {*hkk*}.

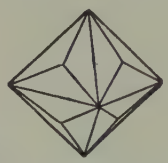


FIG. 85. {*hhl*}.

FIG. 86. {*hkl*}.

intercepts upon the other two, which are equal, while with {*hkk*} the intercept on the third axis is *less* than the intercepts upon the other two. Figure 85 represents the trisoctahedron {221}, a form which occurs on some crystals of galena.

Hexoctahedron {hkl}. The general form of the hexoctahedral class consists of forty-eight faces, the symbols of which may be derived from the form symbol by taking six permutations of letters and eight permutations of signs. Fig. 86 represents the hexoctahedron {321}. It sometimes occurs on fluorite crystals as illustrated in Fig. 98.

Combinations. The cube, octahedron, and dodecahedron are much more common than the other forms. They occur alone and in combination with each other. See Figs. 423–426, page 267.

The hexoctahedron, trisoctahedron, and tetrahexahedron usually occur as small faces modifying simple forms.

Galena, garnet, fluorite, and magnetite are given as typical examples for study and practice.

Examples

Galena. Usual forms: $a\{100\}$, $o\{111\}$. Interfacial angles: $aa(100:010) = 90°0'$; $oo(111:1\bar{1}1) = 70°\ 32'$; $ao(100:111) = 54°\ 44'$. Figures 87 to 91 represent usual combinations varying from the cube alone to the octahedron alone.

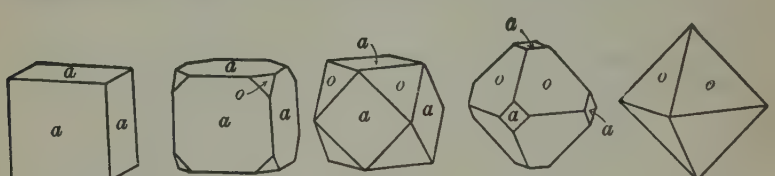


Fig. 87. Fig. 88. Fig. 89. Fig. 90. Fig. 91.

Figs. 87–91.—Galena.

Garnet. Usual forms: $d\{110\}$, $n\{211\}$. Interfacial angles: $dd\{110:101) = 60°\ 0'$; $nn(211:121) = 33°\ 33\frac{1}{2}'$; $nn(211:2\bar{1}1) = 48°\ 11\frac{1}{2}'$; $dn(110:211) = 30°\ 0'$. Figures 92 to 95 represent usual combinations varying from the dodecahedron alone to the trapezohedron alone.

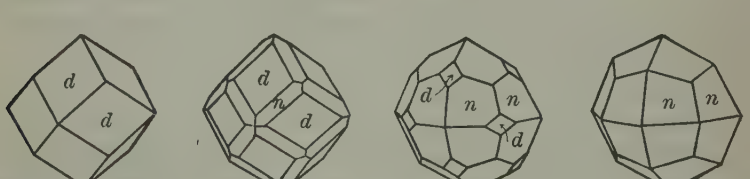


Fig. 92. Fig. 93. Fig. 94. Fig. 95.

Figs. 92–95.—Garnet.

Fluorite. Usual forms: $a\{100\}$, $f\{310\}$, $t\{421\}$. Cleavage parallel to $\{111\}$. Interfacial angles: $aa(100:010) = 90°$; $af(100:310) = 18°\ 26'$ $at(100:421) = 29°\ 12'$. Figures 96 to 99 represent frequent combinations The plane formed by the dotted lines in Fig. 96 represents octahedral cleav

age. Figure 99 represents a twin crystal in which two cubes are twinned about a cube diagonal.

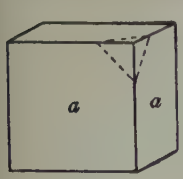


FIG. 96.

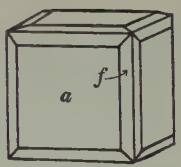


FIG. 97.

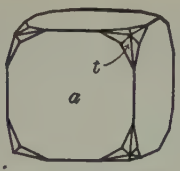


FIG. 98.

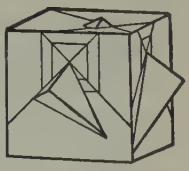


FIG. 99.

FIGS. 96–99.—Fluorite.

Magnetite. Usual forms: $o\{111\}$, $d\{111\}$, $m\{311\}$. Interfacial angles: $oo(111:1\bar{1}1) = 70° 32'$; $dd(110:101) = 60° 0'$; od $(111:110) = 35° 16'$; $om(111:311) = 29° 30'$. Figures 100 to 102 represent typical crystals.

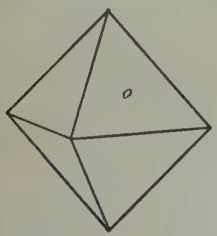


FIG. 100.

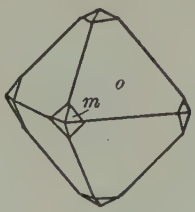


FIG. 101.

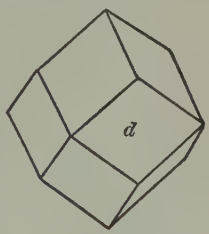


FIG. 102.

Hextetrahedral Class, $4A_3{\cdot}3A_2(3\not{P}_4){\cdot}6P$

The 2-fold axes are mutually perpendicular. The planes of symmetry are diagonal to the 2-fold axes.

(*Tetrahedral hemihedral*)

The axes of 2-fold symmetry (these are also axes of composite 4-fold symmetry, $\not{P}_4$) are the axes of reference.

List of Forms in the Hextetrahedral Class

Cube	6 faces	{100}
Dodecahedron	12 faces	{110}
Tetrahexahedron	24 faces	{hk0}
Tetrahedrons	4 faces	{111}, {1$\bar{1}$1}
Deltohedrons	12 faces	{hhl}, {h$\bar{h}$l}
Tristetrahedrons	12 faces	{hkk}, {h$\bar{k}$k}
Hextetrahedrons	24 faces	{hkl}, {h$\bar{k}$l}

[In the above symbols $h>k>l$]

The first four forms are geometrically different from the corresponding forms in the hexoctahedral class and hence are described below.

Tetrahedrons {111}, {$1\bar{1}1$}. This is the regular tetrahedron of geometry the interfacial angles being 109° 28′ (Fig. 103). The positive and negative forms are exactly alike except in position. The two forms {111} and {$1\bar{1}1$} in equal combination form an octahedron geometrically and therefore they are said to be complementary. The tetrahedron occurs on tetrahedrite and sphalerite.

Deltohedrons {hhl}, {$h\bar{h}l$}. These two forms are also positive and negative according to the octant in which they occur. Fig.

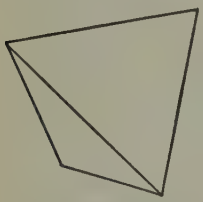


FIG. 103. {111}.

FIG. 104. {*hhl*}.

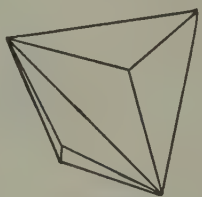


FIG. 105. {*hkk*}.

FIG. 106. {*hkl*}.

104 represents a positive form. The name refers to the deltoid shape of the faces.

Tristetrahedrons {hkk}, {$h\bar{k}k$}. These forms resemble three-faced pyramids built upon each tetrahedral face, hence the name, tristetrahedron. The two forms, which occur in alternate octants, are distinguished as positive and negative. Fig. 105 represents a positive form.

Hextetrahedrons {hkl}, {$h\bar{k}l$}. The general form is a 24-faced form called the hextetrahedron as it apparently consists of a 6-faced pyramid built upon each face of a tetrahedron. (Fig. 106.) The two forms given are distinguished as positive and negative. They occur in alternate octants.

Combinations. Crystals of this class usually have a tetrahedral aspect. The best example is furnished by tetrahedrite.

Sphalerite also belongs to this class, but the crystals are usually distorted.

Example

Tetrahedrite. Usual forms: $o\{111\}$, $o_1\{1\bar{1}1\}$, $n\{211\}$, $d\{110\}$. Interfacial angles: $oo(111:\bar{1}11) = 109° 28'$; $nn(211:121) = 33° 33\frac{1}{2}'$; $no(211:111) = 19° 28'$; $do(110:\bar{1}11) = 35° 16'$. Figs. 107 to 110 represent usual types of tetrahedrite crystals.

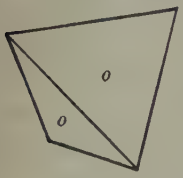


FIG. 107.

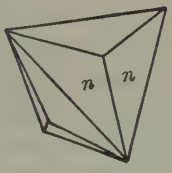


FIG. 108.

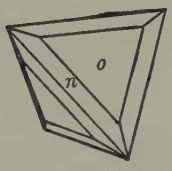


FIG. 109.

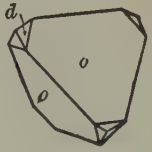


FIG. 110.

FIGS. 107–110.—Tetrahedrite.

Diploidal Class. $4A_3(4\mathcal{A}_6)\cdot 3A_2\cdot 3P\cdot C$

(Pentagonal hemihedral)

The planes of symmetry are mutually perpendicular. Their intersections are the 2-fold axes. The 3-fold axes are also composite 6-fold axes.

The axes of 2-fold symmetry are the axes of reference.

List of Forms in the Diploidal Class

Cube	6 faces	{100}
Octahedron	8 faces	{111}
Dodecahedron	12 faces	{110}
Pyritohedrons	12 faces	{hk0}, {kh0}
Trisoctahedron	24 faces	{hhl}
Trapezohedron	24 faces	{hkk}
Diploids	24 faces	{hkl}, {khl}

[In above symbols $h>k>l$]

Of these forms, all but the pyritohedron and diploid are geometrically similar to those of the preceding class.

Pyritohedrons {hk0}, {kh0}. The pyritohedron is so named because it is common on the mineral pyrite. The two forms given are arbitrarily distinguished as positive and negative. On

pyrite the most common form is the positive pyritohedron {210}, represented by Fig. 111. The faces of the pyritohedron are not regular pentagons. A form with twelve faces each a regular pentagon is impossible as a crystal form, for it has axes of 5-fold symmetry (see p. 136).

Fig. 111. {*hk*0}.

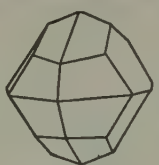


Fig. 112. {*hkl*}.

Diploids {hkl}, {khl}. The general form is a 24-faced form, the faces of which lie in pairs astride the planes of symmetry, hence the name, diploid, which means double. The two congruent forms {*hkl*} and {*khl*} are distinguished as positive and negative. Figure 112 represents the positive diploid {321}.

Pyrite is the only common example of this class.

Examples

Pyrite. Usual forms: *a*{100}, *e*{210}, *o*{111}, *s*{321}, *n*{211}. Interfacial angles: *ae*(100:210) = 26° 34′; *ee*(210:2$\bar{1}$0) = 53° 8′; *ee* (210:102) = 66° 25′; *eo*(210:111) = 39° 14′; *ao*(100:111) = 54° 44′; *se*(321:210) =

Fig. 113.

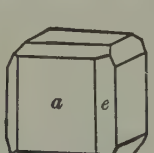


Fig. 114.

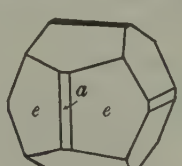


Fig. 115.

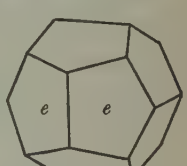


Fig. 116.

Fig. 117.

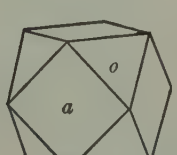


Fig. 118.

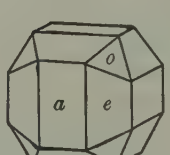


Fig. 119.

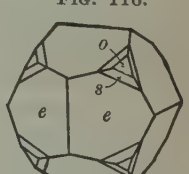


Fig. 120.

Figs. 113–120.—Pyrite.

17° 1½′; *sa*(321:100) = 36° 42′; *so*(321:111) = 22° 12½′; *an*(100:211) = 35° 16′; *on*(111:211) = 19° 28′; Figs. 113 to 120 represent common tpyes of pyrite crystals. The cube faces are usually striated as shown in Fig. 113

Graphic Determination of Indices in the Isometric System. There are no axial ratios to be determined but simply the indices of the faces. A plan and elevation are made from the interfacial angles. Figure 121 represents pyrite with the faces *a*, *e*, and *o*. The intercepts of the *e*-face in terms of the unit are seen to be $1a_1 : 2a_2 : \infty a_3$ which reduces to the Miller symbol (210).

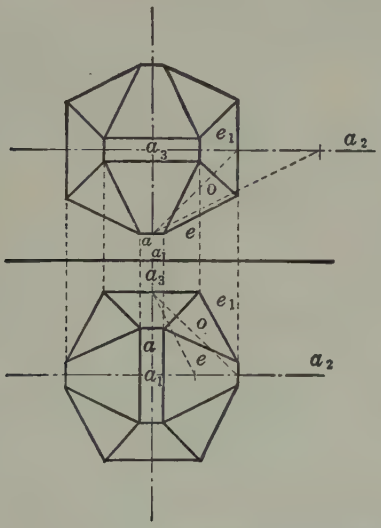


FIG. 121.—Plan and elevation of a pyrite crystal.

The intercepts of e_1 are: $\infty a_1 : \frac{1}{2}a_2 : 1a_3$ and the indices (021). And by means of a side elevation the intercepts of the face (102) could also be determined.

10. THE TETRAGONAL SYSTEM

The tetragonal system includes all crystals with a single axis of 4-fold symmetry (A_4) or a composite 4-fold axis ($\mathcal{A}_4$) of symmetry which is taken as an axis of reference. The other two axes of reference are interchangeable. The axes are designated

$a_1 : a_2 : \dot{c}$, the unit lengths of a_1 and a_2 each equal to unity and the unit length of $\dot{c}$ either greater or less than unity. The c-axis is A_4 (or $\dot{P}_4$). Figure 122 represents the axes for zircon and Fig. 123, those for apophyllite.

Of the seven classes of the tetragonal system only one is treated here.

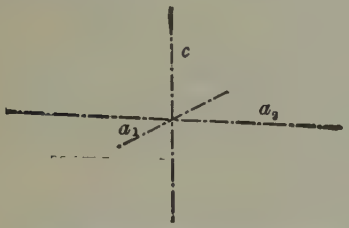


FIG. 122.—Tetragonal axes of reference for zircon.

FIG. 123.—Tetragonal axes of reference for apophyllite.

Ditetragonal Bipyramidal Class. $A_4.4A_2.5P.C$

(*Holohedral*)

The 2-fold axes are normal to the 4-fold axis. Four vertical planes of symmetry intersect each other at angles of 45°, and the fifth is normal to these four.

The axis of 4-fold symmetry is the c-axis. As there are four axes of 2-fold symmetry at 45° to each other, either pair at right angles to each other may be selected as the lateral axes.

List of Forms in the Ditetragonal Bipyramidal Class

Pinacoid	2 faces	{001}	(Basal pinacoid)
Tetragonal prism	4 faces	{100}	(Prism of second order)
Tetragonal prism	4 faces	{110}	(Prism of first order)
Ditetragonal prism	8 faces	{hk0}	(Ditetragonal prism)
Tetragonal bipyramid	8 faces	{h0l}	(Pyramid of second order)
Tetragonal bipyramid	8 faces	{hhl}	(Pyramid of first order)
Ditetragonal bipyramid	16 faces	{hkl}	(Ditetragonal pyramid)

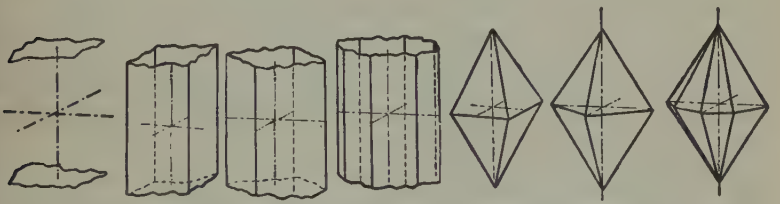
Pinacoid {**001**} (Basal pinacoid). This form consists of two parallel faces, an upper one and a lower one (Fig. 124).

Tetragonal Prism {**100**} (Prism of the second order). This is an open form similar to {110} except in position (Fig. 125).

Tetragonal Prism {**110**} (Prism of the first order). This is an open form with four faces each parallel to the vertical axis (Fig. 126).

Ditetragonal Prism {**hk0**} (Ditetragonal prism). An open form consisting of eight faces, each parallel to the vertical axis (Fig. 127). The faces meet in angles which are alternately equal.

Tetragonal Bipyramid {**h0l**} (Pyramid of the second order). A form consisting of eight faces each parallel to one lateral axis (Fig. 128). This form and {*hhl*} are identical except in position.



124{001}. 125{100}. 126{110}. 127{*hk*0}. 128{*h*0*l*}. 129{*hhl*}. 130{*hkl*}.

FIGS. 124–130.—The seven type forms of the ditetragonal bipyramidal class.

Tetragonal Bipyramid {**hhl**} (Pyramid of the first order). This form cuts the lateral axes at equal distances (Fig. 129). The faces are isosceles triangles in the ideal form.

Ditetragonal Bipyramid {**hkl**} (Ditetragonal pyramid). The general form consists of sixteen faces; the faces in the ideal form are scalene triangles (Fig. 130). The angles over alternate polar edges are equal.

Combinations. The bipyramids are closed forms, but the prisms and pinacoids are open forms, and hence must occur in combination. In habit, tetragonal crystals are usually prismatic, pyramidal, or tabular, but equidimensional pseudo-octahedral and pseudo-cubic crystals are not uncommon.

Examples

Zircon, apophyllite, and vesuvianite are given as typical examples for study and practice.

Zircon. $\dot{c} = 0.640$. Usual forms: $m\{110\}$, $a\{100\}$, $p\{111\}$, $u\{331\}$, $x\{311\}$. Interfacial angles: $mp(110:111) = 47° 50'$; $mm(110:1\bar{1}0) = 90° 0'$; $ma(110:100) = 45° 0'$; $ap(100:111) = 61° 40'$; $mu(110:331) = 20° 12'$; $xx(311:3\bar{1}1) = 32° 57'$; $pp(111:1\bar{1}1) = 56° 40'$. Figures 131 to 134 represent the usual combinations and habits.

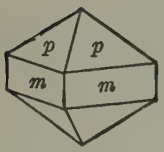


Fig. 131.

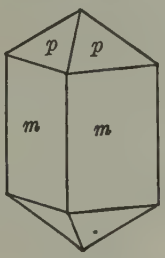


Fig. 132.

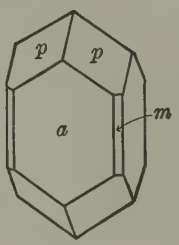


Fig. 133.

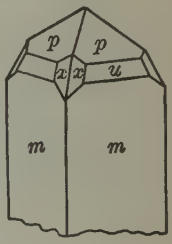


Fig. 134.

Figs. 131–134.—Zircon.

Apophyllite. $\dot{c} = 1.251$. Usual forms: $a\{100\}$, $c\{001\}$, $p\{111\}$, $y\{110\}$. Cleavage parallel to $c\{001\}$. Interfacial angles: $co(001:111) = 60° 32'$; $ap(100:111) = 52° 0'$; $pp(111:1\bar{1}1) = 76° 0'$; $ay(100:310) = 18° 26'$. Figures 135 to 138 represent the usual combinations and habits.

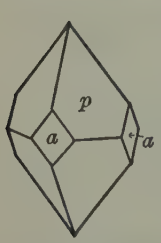


Fig. 135.

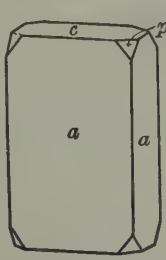


Fig. 136.

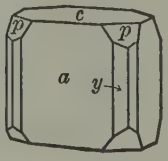


Fig. 137.

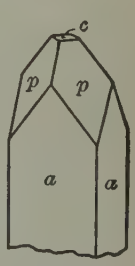


Fig. 138.

Figs. 135–138.—Apophyllite.

Vesuvianite $\dot{c} = 0.537$. Usual forms: $p\{111\}$, $m\{110\}$, $a\{100\}$, $c\{001\}$, $t\{331\}$, $s\{311\}$. Interfacial angles: $pp(111:1\bar{1}1) = 50° 39'$; $cp(001:111) =$

37° 13½′; ap(100:111) = 64° 40½′; am(100:110) = 45° 0′; mt(110:331) = 23° 41½′; as(100:311) = 35° 10′. Figures 139 to 142 illustrate typical crystals.

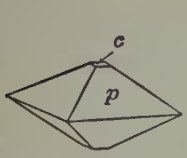


FIG. 139.

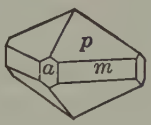


FIG. 140.

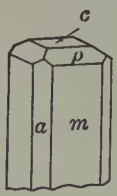


FIG. 141.

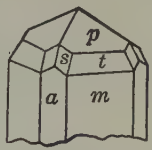


FIG. 142.

FIGS. 139–142.—Vesuvianite.

Graphic Determination of Indices and Axial Ratio in the Tetragonal System. A plan and elevation of a zircon crystal are shown in Fig. 143. The unit bipyramid {111} is the p face; the problem is to determine the symbol of u and the axial ratio $a : c$. In the elevation, lines parallel to the projections of p and u are drawn

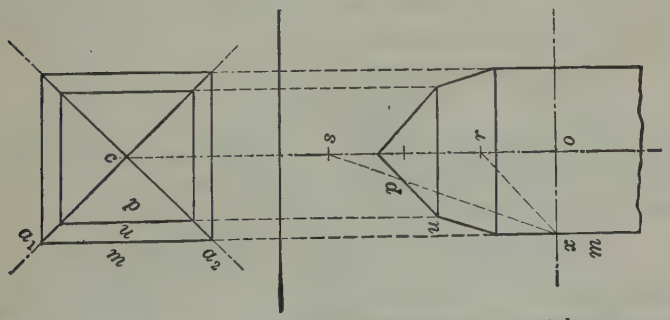


FIG. 143.—Plan and elevation of a zircon crystal.

through the point x to intersect the c-axis. Then the distance os is equal to 3 times the distance or. Therefore the symbol of u is $1a_1{:}1a_2{:}3c$ or (331). The distance or is equal to about 0.64 of the distance ca_1 (in the plan); therefore the axial ratio $a : c$ is 1 : 0.64. (It will be noted that ox is the foreshortened ca_1.)

11. THE HEXAGONAL SYSTEM[1]

The hexagonal system includes all crystals with a single axis of 3-fold or 6-fold symmetry. (In two classes the 3-fold axis is also a composite axis of 6-fold symmetry.) Four axes of reference, three interchangeable ones in a plane at right angles to the fourth, are used. The positive ends of the three lateral axes make angles of 120° with each other, as shown in Fig. 144. The index on the third axis is always equal to the sum of the first two with the sign changed, so that the Miller symbol for the general form is $\{h \cdot k \cdot \overline{h+k} \cdot l\}$, in which h is always greater than k. The axes may be designated $a_1 : a_2 : a_3 : c$, in which the unit lengths on a_1, a_2, and a_3 are unity and the unit length on c either greater or less than unity. The axis of 3-fold or 6-fold symmetry is always taken as the c-axis.

FIG. 144.—Hexagonal axes of reference.

Dihexagonal Bipyramidal Class. $A_6 \cdot 6A_2 \cdot 7P \cdot C$

(*Holohedral*)

The 2-fold axes are normal to the 6-fold axes. There are six vertical planes of symmetry at angles of 30° apart. The other plane of symmetry is perpendicular to these six.

List of Forms in the Dihexagonal Bipyramidal Class

Pinacoid	2 faces	$\{0001\}$	(Basal pinacoid)
Hexagonal prism	6 faces	$\{10\bar{1}0\}$	(Prism of 1st order)
Hexagonal prism	6 faces	$\{11\bar{2}0\}$	(Prism of 2d order)
Dihexagonal prism	12 faces	$\{h \cdot k \cdot \overline{h+k} \cdot 0\}$	(Dihexagonal prism)
Hexagonal bipyramid	12 faces	$\{h0\bar{h}l\}$	(Pyramid of 1st order)
Hexagonal bipyramid	12 faces	$\{h \cdot h \cdot \overline{2h} \cdot l\}$	(Pyramid of 2d order)
Dihexagonal bipyramid	24 faces	$\{h \cdot k \cdot \overline{h+k} \cdot l\}$	(Dihexagonal pyramid)

[In the above symbols $h > k$.]

[1] Classes 16, 17, 18, 19, and 20 (see p. 80) of the hexagonal system constitute a rhombohedral subsystem. They may be referred either to the four axes of reference mentioned or to three interchangeable axes at equal oblique angles (like the legs of a 3-legged stool). These five classes are sometimes treated as a separate system, but they are so closely related to the other seven classes that they are here retained in the hexagonal system.

Pinacoid {**0001**} (Basal pinacoid). This form consists of two opposite parallel faces which are usually regular hexagons. (Fig. 145.)

Hexagonal Prism {**10$\bar{1}$0**} (Prism of the first order). The faces are in a vertical zone and intersect at angles of 60°. (Fig. 146.)

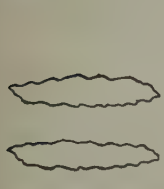


FIG. 145 {0001}.

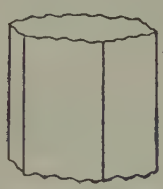


FIG. 146 {10$\bar{1}$0}.

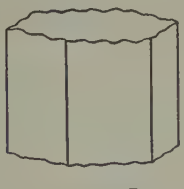


FIG. 147 {11$\bar{2}$0}.

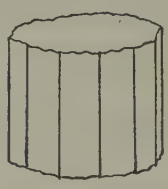


FIG. 148 {$h{\cdot}k{\cdot}\overline{h+k}{\cdot}0$}.

Hexagonal Prism {**11$\bar{2}$0**} (Prism of the second order). This form is similar to {10$\bar{1}$0} except in position. (Fig. 147.)

Dihexagonal Prism {**h·k·$\overline{\text{h+k}}$·0**}. All the faces are in a vertical zone, each being parallel to the vertical axis. Alternate angles are equal. (Fig. 148.)

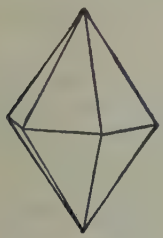


FIG. 149 {$h0\bar{h}l$}.

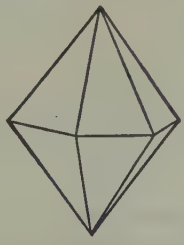


FIG. 150 {$h{\cdot}h{\cdot}\overline{2h}{\cdot}l$}.

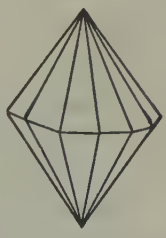


FIG. 151 {$h{\cdot}k{\cdot}\overline{h+k}{\cdot}l$}.

Hexagonal Bipyramid {**h0$\bar{\text{h}}$l**} (Pyramid of the first order). The faces cut two of the lateral axes, but are parallel to the third. (Fig. 149.)

Hexagonal Bipyramid {**h·h·$\overline{\text{2h}}$·l**} (Pyramid of the second order). The faces cut two of the lateral axes at equal but greater distances than the third lateral axis. (Fig. 150.) This form differs from {**h0$\bar{\text{h}}$l**} only in position.

Dihexagonal Bipyramid $\{h\cdot k\cdot \overline{h+k}\cdot l\}$ (Dihexagonal pyramid). This form consists of 24 faces (scalene triangles in the ideal form), each of which cuts the four axes at unequal distances. The angles over alternate polar edges are equal. (Fig. 151.)

Combinations. The habit is prismatic, pyramidal, or tabular. Simple combinations are the rule in this class. As beryl is the only common mineral belonging to this class, it is the only example given for practice.

Example

Beryl. $\dot{c} = 0.498$. Usual forms: $c\{0001\}$, $m\{10\bar{1}0\}$, $p\{10\bar{1}1\}$, $s\{11\bar{2}1\}$, $v\{21\bar{3}1\}$. Interfacial angles: $mm(10\bar{1}0:01\bar{1}0) = 60°\ 0'$; $cs(0001:11\bar{2}1) = 44°\ 56'$; $cp(0001:10\bar{1}1) = 29°\ 57'$; $mv(10\bar{1}0:21\bar{3}1) = 37°\ 49'$; $ms(10\bar{1}0:11\bar{2}1) = 52°\ 17'$. Figures 152 and 153 are the ordinary combinations. Figure 154 has in addition the general form $v\{21\bar{3}1\}$. Figure 155 represents beryl of tabular habit, which is rare as compared with the prismatic habit.

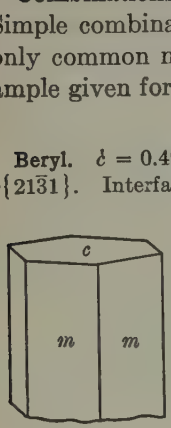


Fig. 152.

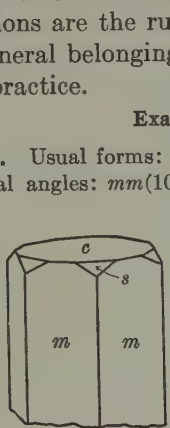


Fig. 153.

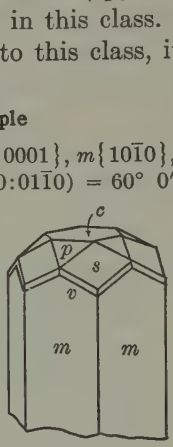


Fig. 154.

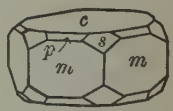


Fig. 155.

Figs. 152–155.—Beryl.

Hexagonal Scalenohedral Class. $A_3(AP_6)\cdot 3A_2\cdot 3P\cdot C$

(Rhombohedral hemihedral)

The planes of symmetry intersect each other in the 3-fold axis and the 2-fold axes are diagonal to the planes of symmetry. The lateral axes of reference are the axes of 2-fold symmetry and the *c*-axis, the axis of 3-fold symmetry. The 3-fold axis is also a composite 6-fold axis.[1]

[1] It is possible to refer crystals of this class and the next two classes to three interchangeable axes of reference at oblique angles to each other. In this case, the Miller symbol has three indices *hkl* and the axial element is α, the oblique angle between the axes, which varies for each particular mineral. (See footnote on p. 102.)

List of Forms in the Hexagonal Scalenohedral Class

Pinacoid	2 faces	$\{0001\}$	(Basal pinacoid)
Hexagonal prism	6 faces	$\{11\bar{2}0\}$	(Prism of 2d order)
Hexagonal prism	6 faces	$\{10\bar{1}0\}$	(Prism of 1st order)
Dihexagonal prism	12 faces	$\{h\cdot k\cdot \overline{h+k}\cdot o\}$	(Dihexagonal prism)
Rhombohedrons	6 faces	$\{h0\bar{h}l\}$, $\{0h\bar{h}l\}$	(Rhombohedrons)
Hexagonal bipyramid	12 faces	$\{h\cdot h\cdot \overline{2h}\cdot l\}$	(Pyramid of 2d order)
Scalenohedrons	12 faces	$\{h\cdot k\cdot \overline{h+k}\cdot l\}$, $\{k\cdot h\cdot \overline{k+h}\cdot l\}$	(Scalenohedrons)

[In the above symbols $h>k$]

Pinacoid $\{0001\}$ (Basal pinacoid). There are two faces at opposite ends of the vertical axis. (Fig. 145.)

Hexagonal Prism $\{10\bar{1}0\}$ (Prism of the first order). There are six faces in one zone meeting at angles of 60°. (Fig. 146.)

Hexagonal Prism $\{11\bar{2}0\}$ (Prism of the second order). This form is exactly like $\{10\bar{1}0\}$ except in position. (Fig. 147.)

Dihexagonal Prism $\{h\cdot k\cdot \overline{h+k}\cdot 0\}$. There are twelve faces in a vertical zone. (Fig. 148.) Alternate angles are equal.

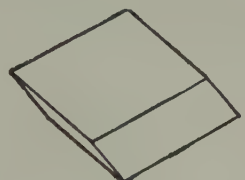


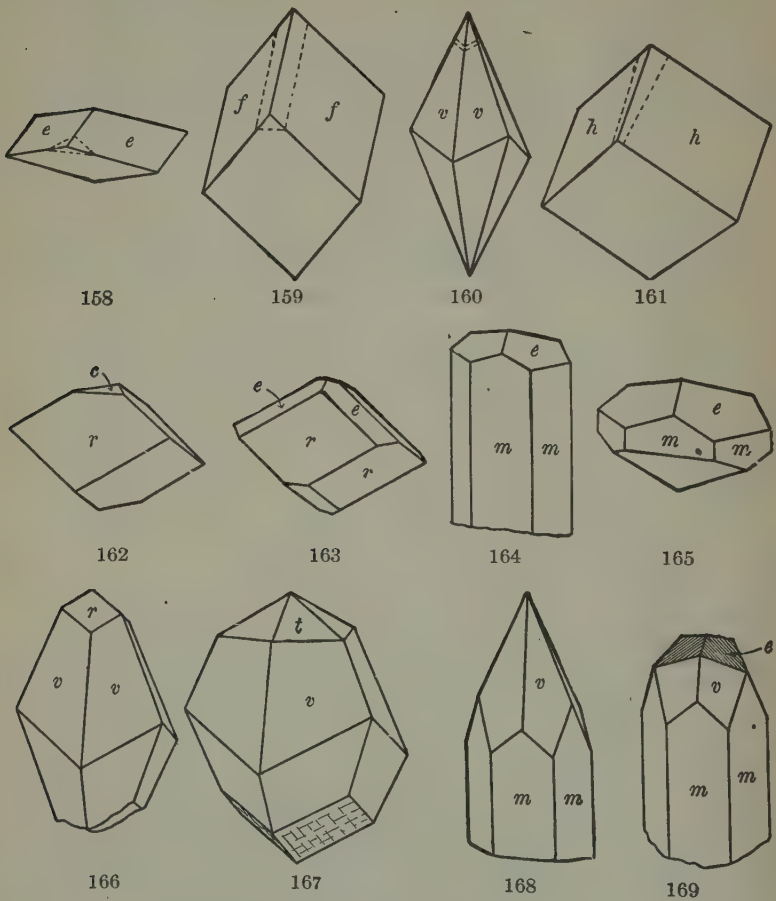
Fig. 156 $\{h0\bar{h}l\}$.

Fig. 157 $\{h\cdot k\cdot \overline{h+k}\cdot l\}$

Rhombohedrons $\{h0\bar{h}l\}$, $\{0h\bar{h}l\}$. A rhombohedron consists of six rhombic faces, and is like a cube distorted in the direction of one of its diagonals. A rhombohedron is distinguished as acute or obtuse according to whether the supplement angle over the polar edges is greater or less than 90°. The rhombohedron with faces in the middle front, right rear, and left rear dodecants is called positive and has the symbol $\{h0\bar{h}l\}$, while the rhombohedron with faces in the right front, left front, and middle rear dodecants is called negative and has the symbol $\{0h\bar{h}l\}$. Figure 156, an obtuse positive rhombohedron, represents the cleavage rhombohedron of calcite.

Hexagonal Bipyramid $\{h\cdot h\cdot \overline{2h}\cdot l\}$ (Pyramid of the second order). This form consists of twelve faces, each an isosceles

triangle. (Figure 150.) Hexagonal bipyramids are very rare forms for calcite.



FIGS. 158–169.—Calcite.

Scalenohedrons $\{h{\cdot}k{\cdot}\overline{h+k}{\cdot}l\}, \{k{\cdot}h{\cdot}\overline{k+h}{\cdot}l\}$. The general form of this class is a 12-sided figure, each face of which is a scalene triangle. There are three kinds of edges: short polar, long

polar, and middle edges, each with their characteristic interfacial angles. The $\{h\cdot k\cdot \overline{h+k}\cdot l\}$ form is called positive and the $\{k\cdot h\cdot \overline{k+h}\cdot l\}$ form, negative. Figure 157 is a positive scalenohedron.

Example

Calcite. $c = 0.854$. Usual forms: $c\{0001\}$, $m\{1010\}$, $a\{11\bar{2}0\}$, $e\{01\bar{1}2\}$, $r\{10\bar{1}1\}$, $f\{02\bar{2}1\}$, $h\{03\bar{3}2\}$, $M\{40\bar{4}1\}$, $v\{21\bar{3}1\}$, $y\{32\bar{5}1\}$, $t\{21\bar{3}4\}$. Cleavage parallel to r. Interfacial angles: $ee(01\bar{1}2:\bar{1}012) = 45°\ 3'$; $em(01\bar{1}2:10\bar{1}0) = 63°\ 45'$; $rr(10\bar{1}1:\bar{1}101) = 74°\ 55'$; $rm(10\bar{1}1:10\bar{1}0) = 45°\ 23\frac{1}{2}'$; $ff(02\bar{2}1:\bar{2}021) = 101°\ 9'$; $fm(02\bar{2}1:01\bar{1}0) = 26°\ 53'$; $MM(40\bar{4}1:\bar{4}401) = 114°\ 10'$; $Mm(40\bar{4}1:10\bar{1}0) = 14°\ 13'$; $hh(03\bar{3}2:\bar{3}302) = 91°\ 42'$; $vv(21\bar{3}1:\bar{2}3\bar{1}1) = 75°\ 22'$; $vv(21\bar{3}1:3\bar{1}21) = 35°\ 36'$; $vv(21\bar{3}1:12\bar{3}1) = 47°\ 1'$; $yy(32\bar{5}1:\bar{3}5\bar{2}1) = 70°\ 59'$; $yy(32\bar{5}1:5\bar{2}31) = 45°\ 32'$; $vy(21\bar{3}1:32\bar{5}1) = 8°\ 53'$; $rv(10\bar{1}1:21\bar{3}1) = 29°\ 1\frac{1}{2}'$; $mv(10\bar{1}0:21\bar{3}1) = 28°\ 4'$; $tt(21\bar{3}4:3\bar{1}24) = 20°\ 36\frac{1}{2}'$; $te(21\bar{3}4:01\bar{1}2) = 20°\ 57\frac{1}{2}'$.

Figures 158 to 169 represent some of the common types of calcite crystals. The dotted lines in the figures represent cleavage planes which aid in distinguishing positive and negative forms.

Ditrigonal Pyramidal Class. $A_3 \cdot 3P$

(Hemimorphic tetartohedral)

The three planes of symmetry intersect each other in the 3-fold axis of symmetry.

The lateral axes of reference are diagonal to the planes of symmetry.

List of Forms in the Ditrigonal Pyramidal Class

Pedions	1 face	$\{0001\}$,	$\{000\bar{1}\}$ (Basal planes)
Trigonal prisms	3 faces	$\{10\bar{1}0\}$,	$\{01\bar{1}0\}$ (Prisms of 1st order)
Hexagonal prism	6 faces	$\{11\bar{2}0\}$	(Prism of 2d order)
Ditrigonal prisms	6 faces	$\{h\cdot k\cdot \overline{h+k}\cdot 0\}$	$\{k\cdot h\cdot \overline{k+h}\cdot 0\}$ (Ditrigonal prisms)
Trigonal pyramids	3 faces	$\{h0\bar{h}l\}$,	$\{h0\bar{h}\bar{l}\}$ Pyramids of 1st order
Trigonal pyramids	3 faces	$\{0h\bar{h}l\}$	$\{0hh\bar{l}\}$ (Pyramid of 1st order)
Hexagonal pyramids	6 faces	$\{h\cdot h\cdot \bar{2}h\cdot l\}$	$\{h\cdot h\cdot \bar{2}h\cdot \bar{l}\}$ (Hemimorphic pyramids)
Ditrigonal pyramids	6 faces	$\{h\cdot k\cdot \overline{h+k}\cdot l\}$	$\{h\cdot k\cdot \overline{h+k}\cdot \bar{l}\cdot\}$ (Hemimorphic pyramid
Ditrigonal pyramids	6 faces	$\{k\cdot h\cdot \overline{k+h}\cdot l\}$	$\{k\cdot h\cdot \overline{k+h}\cdot \bar{l}\}$
[In the above symbols $h > k$]			(Hemimorphic pyramids)

Pedions $\{0001\}$, $\{000\bar{1}\}$. Each of these forms consists of a single face, a positive pedion at the upper end of the crystal and a negative pedion at the lower end.

Trigonal Prisms $\{10\bar{1}0\}$, $\{01\bar{1}0\}$. These two forms differ only in position. Figure 170 shows $\{01\bar{1}0\}$.

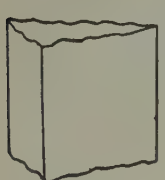


FIG. 170
$\{01\bar{1}0\}$.

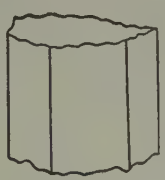


FIG. 171
$\{h{\cdot}k{\cdot}\bar{h}+k{\cdot}o\}$.

FIG. 172
$\{0hhl\}$.

FIG. 173
$\{h{\cdot}k{\cdot}\bar{h}+\bar{k}{\cdot}l\}$.

Hexagonal Prism $\{11\bar{2}0\}$, (Second order prism).

Ditrigonal Prisms $\{h{\cdot}k{\cdot}\overline{h+h}.0\}$, $\{k.h.\overline{k+h}.0\}$. The angles over alternate angles are equal. Fig. 171.

Trigonal Pyramids $\{h0\bar{h}l\}$, $\{h0\overline{\bar{h}l}\}$, $\{0h\overline{\bar{h}l}\}$, $\{0h\bar{h}\bar{l}\}$ (Hemimorphic trigonal pyramids of the first order). Each of these forms consists of three faces. They are distinguished as positive and negative, and upper and lower. Figure 172 represents an upper negative trigonal pyramid.

Hexagonal Pyramids $\{h{\cdot}h{\cdot}\overline{2h}{\cdot}l\}$, $\{h{\cdot}h{\cdot}\overline{2h}{\cdot}\bar{l}\}$ (Hemimorphic hexagonal pyramids). There are six faces each of which cuts two lateral axes at equal but greater distances than the third lateral axis.

Ditrigonal Pyramids $\{h{\cdot}k{\cdot}\overline{h+k}{\cdot}l\}$, $\{h{\cdot}k{\cdot}\overline{h+k}{\cdot}\bar{l}\}$, $\{k{\cdot}h{\cdot}\overline{k+h}{\cdot}\bar{l}\}$, $\{k{\cdot}h{\cdot}\overline{k+h}.\bar{l}\}$ (Hemimorphic ditrigonal pyramids). The general form is a six-faced pyramid with alternate angles equal. The four forms indicated are the positive upper, positive lower, negative upper, and negative lower pyramids. (Fig. 173.)

Example

Tourmaline, a complex boro-silicate, is the best representative of this class.

Tourmaline. $c = 0.447$. Usual forms: $m\{10\bar{1}0\}$, $m_1\{01\bar{1}0\}$, $a\{11\bar{2}0\}$, $r\{10\bar{1}1\}$, $r_1\{01\bar{1}\bar{1}\}$, $o\{02\bar{2}1\}$, $e\{01\bar{1}2\}$, $c_1\{000\bar{1}\}$, $x\{12\bar{3}2\}$. Interfacial

angles: $rr(10\bar{1}1:1101) = 46°\ 52'$; $mr(10\bar{1}0:10\bar{1}1) = 62°\ 40'$; $ma(10\bar{1}0:11\bar{2}0) = 30°\ 0'$; $aa(11\bar{2}0:\bar{1}2\bar{1}0) = 60°0'$; $ee(01\bar{1}2:;\bar{1}012) = 25°2'$; $em_1(01\bar{1}2:01\bar{1}0) : = 75°\ 30\frac{1}{2}'$; $oo(02\bar{2}1:\bar{2}021) = 77°\ 0'$. (Figs. 174–177.)

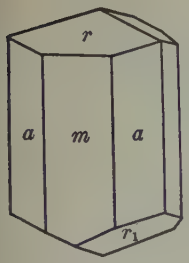


Fig. 174.

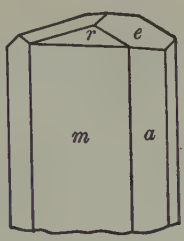


Fig. 175.

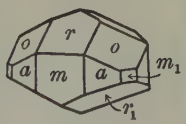


Fig. 176.

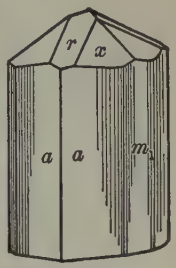


Fig. 177.

Figs. 174–177.—Tourmaline.

Trigonal Trapezohedral Class. $A_3.3A_2$

(Trapezohedral tetartohedral)

The 2-fold axes are perpendicular to the 3-fold axis. The axes of symmetry are the axes of reference.

List of Forms in the Trigonal Trapezohedral Class

Pinacoid	2 faces		{0001}
Hexagonal prism	6 faces		{10$\bar{1}$0}
Ditrigonal prisms	6 faces	{h·k·$\overline{h+k}$·0}	{k·h·$\overline{k+h}$·0}
Trigonal prisms	3 faces	{11$\bar{2}$0}	{$\bar{1}$2$\bar{1}$0}
Rhombohedrons	6 faces	{h0$\bar{h}$l},	{0h$\bar{h}$l}
Trigonal bipyramids	6 faces	{h·h·{2$\bar{h}$·l}	{2h·$\bar{h}$·$\bar{h}$·l}
Trigonal trapezohedrons	6 faces	{h+k·$\bar{k}$·$\bar{h}$·l}	{$\bar{k}$·h+k·$\bar{h}$·l}

[In the above symbols $h > k$.]

The two geometrically new forms for this class are the trigonal bipyramid and trigonal trapezohedron.

Trigonal Bipyramids. Two kinds of trigonal bipyramids are possible for each value of h. They differ only in position. Fig. 178 shows the form $\{h.\ h.\ \bar{2}h.l\}$.

Trigonal Trapezohedrons. The trigonal trapezohedron is a double-ended 6-faced form with the symmetry $A_3.3A_2$. Four

different trapezohedrons are possible for any given value of h and k. Figure 179 represents the form $\{h\cdot k\cdot \overline{h+k}\cdot l\}$.

Example

Quartz. $\dot{c} = 1.099$. Usual forms: $r\{10\bar{1}1\}$, $z\{01\bar{1}1\}$, $m\{10\bar{1}0\}$, $s\{11\bar{2}1\}$, $x\{51\bar{6}1\}, x_1\{61\bar{5}1\}$. Interfacial angles, $mm(10\bar{1}0:01\bar{1}0) = 60°\ 0'$; $mr(10\bar{1}0:10\bar{1}1) = 38°\ 13'$; $mr(01\bar{1}0:10\bar{1}1) = 66°\ 52'$; $rz(10\bar{1}1:01\bar{1}1) = 46°\ 16'$; $rr(10\bar{1}1:\bar{1}101) = 85°\ 46'$; $ms(10\bar{1}0:-11\bar{2}1) = 37°\ 58'$; $mx(10\bar{1}0:51\bar{6}1) = 12°1'$; $mx_1\ (10\bar{1}0:61\bar{5}1) = 12°\ 1'$.

Figures 180–183 represent some of the common varieties of quartz crystals.

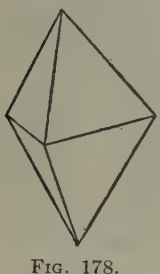


Fig. 178.

Fig. 179.

Graphic Determination of Indices and Axial Ratio in the Hexagonal System. Graphic determinations in this system are illustrated by the plan and elevation of a quartz crystal shown in Fig. 184. The unit face r is $(10\bar{1}1)$, z is $(01\bar{1}1)$, and m is $(10\bar{1}0)$. What is the symbol of M? In the side elevation, draw lines

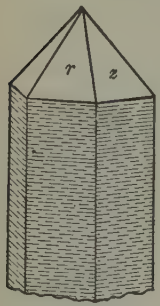


Fig. 180.

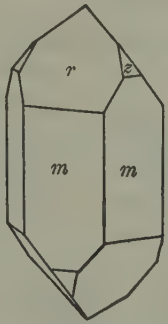


Fig. 181.

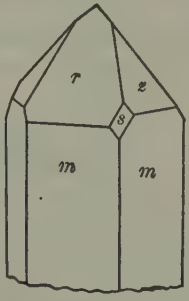


Fig. 182.

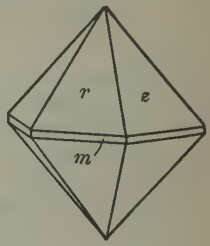


Fig. 183.

Figs. 180–183.—Quartz.

through n parallel to the projections of the r and M faces. These intersect the vertical axis in the points p and q. The distance oq is three times the distance op; therefore the symbol of the M-face is: $1a_1 : \infty a_2 : 1a_3 : 3\dot{c}$ or $30\bar{3}1$.

The axial ratio $\dot{c}$ ($a=1$) is the distance op in terms of oa_1 (in the plan).

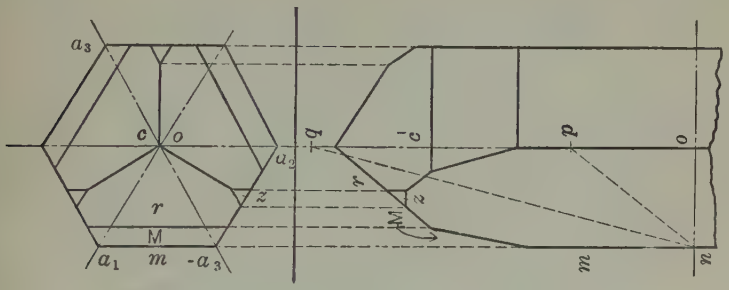


FIG. 184.—Plan and elevation of a quartz crystal.

12. THE ORTHORHOMBIC SYSTEM

The orthorhombic system includes all crystals with three non-interchangeable directions of symmetry at right angles to each other. The axial ratios are $\breve{a}:\bar{b}:\dot{c}$. Conventionally the unit length of b is unity, and the unit length of a always less than unity.

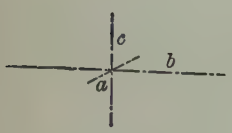


FIG. 185.—Axes of reference for topaz.

FIG. 186.—Axes of reference for barite.

FIG. 187.—Axes of reference for cerussite.

These values for the axial ratios differ for every orthorhombic substance. Figures 185, 186, and 187 represent the unit lengths of the axes for topaz, barite, and cerussite respectively.

Of the three classes of the orthorhombic system, only one is discussed here.

Rhombic Bipyramidal Class. $3A_2 \cdot 3P \cdot C$

(Holohedral)

The three planes of symmetry are mutually perpendicular, and their intersections are the axes of 2-fold symmetry. The three axes of 2-fold symmetry are the axes of reference. The selection of the *c*-axis is arbitrary, but of the other two, the unit on *a* is always shorter than the unit on *b*.

List of Forms in the Rhombic Bipyramidal Class

Pinacoid	2 faces	{**001**}	(Basal pinacoid)
Pinacoid	2 faces	{**010**}	(Brachypinacoid)
Pinacoid	2 faces	{**100**}	(Macropinacoid)
Rhombic prism	4 faces	{**hk0**}	(Rhombic prism)
Rhombic prism	4 faces	{**h0l**}	(Macrodome)
Rhombic prism	4 faces	{**0kl**}	(Brachydome)
Rhombic bipyramid	8 faces	{**hkl**}	(Rhombic pyramid)[1]

Pinacoid {001} (Basal pinacoid). This form may be called the *top pinacoid* (Fig. 188). The symbol is written {001} instead of {00l}, for only one form of the kind is possible in this class.

Pinacoid {010} (Brachypinacoid). This form, consisting of two parallel faces, one on the right and one on the left, may be called the *side pinacoid* (Fig. 189). The symbol is written {010} instead of {0*k*0}.

Pinacoid {100} (Macropinacoid). This form may be called the *front pinacoid* as it consists of two opposite parallel faces, one in front and one behind (Fig. 190). As there is only one pinacoid of this kind possible, the symbol {100} is used instead of {*h*00}.

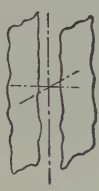
Rhombic Prism {hk0} (Rhombic prism). An open form consisting of four vertical faces (Fig. 191). For each substance crystallizing in the orthorhombic system a whole series of prisms is possible ranging from {010} to {100}. The unit prism is {110}.

[1] These names are used by some authors.

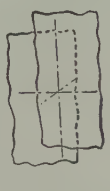
Rhombic Prism {h0l} (Macrodome). A horizontal open form composed of four faces each parallel to the *b*-axis (Fig. 192). There is also a series varying from {001} to {010} for all possible values of *h* and *l*.

Rhombic Prism {0kl} (Brachydome). A horizontal open form composed of four faces each parallel to the *a*-axis (Fig. 193). There is a series of all possible rational values of *k* and *l*.

FIG. 188. {001}

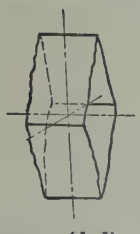


189. {010}



190. {100}

191. {*hk*0}.



192. {*h*0*l*}

193. {0*kl*}.

194. {*hkl*}.

FIGS. 188–194.—The seven type forms of the rhombic bipyramidal class.

Rhombic Bipyramid {hkl} (Rhombic pyramid). The general form of this class consists of eight faces, which in the ideal form are scalene triangles (Fig. 194). For any one substance there is a great variety of forms possible depending upon various simple rational values of *h*, *k*, and *l*. If *h* and *k* are equal we have {*hhl*}, of which there is a series with varying values of *l*. As these forms are in a vertical zone with the unit prism {110}, they are called bipyramids of the unit-series. {111} is the unit bipyramid.

Combinations. Only the bipyramids can occur alone. All other crystals are combinations of two or more forms. There

are manifold combinations and consequently a great variety in the habit. The most common are tabular, prismatic, and pyramidal, but some crystals cannot be placed under either of these. Pseudo-hexagonal orthorhombic crystals are common, but careful measurement distinguishes them from hexagonal crystals.

Examples

Examples of orthorhombic crystals are numerous among both minerals and prepared compounds. Barite ($BaSO_4$) and topaz ($Al_2F_2SiO_4$) are given as typical examples for study and practice in working out the forms.

Barite. $\breve{a}:\bar{b}:\dot{c} = 0.815:1:1.313$. Usual forms: $c\{001\}$, $m\{110\}$, $b\{010\}$, $o\{011\}$, $u\{101\}$, $d\{102\}$, $l\{104\}$. Cleavage parallel to c and m. Interfacial angles: $mm(110:1\bar{1}0) = 78°\ 22\frac{1}{2}'$; $cm(001:110) = 90°$; $co(001:011) =$

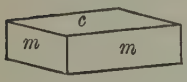


Fig. 195.

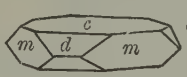


Fig. 196.

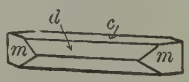


Fig. 197.

Fig. 198.

Figs. 195–198.—Barite.

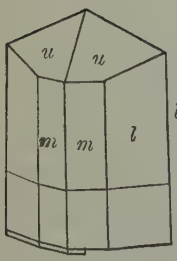


Fig. 199.

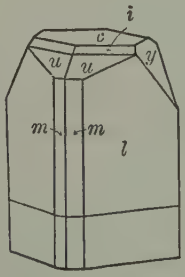


Fig. 200.

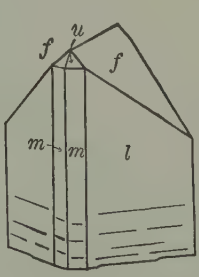


Fig. 201.

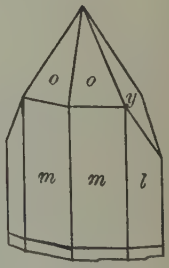


Fig. 202.

Figs. 199–202.—Topaz.

52° 43′; $cu(001:101) = 58°\ 10\frac{1}{2}'$; $cd(001:102) = 38°\ 51'$; $cl(001:104) = 21°\ 56'$. Figures 195 to 198 are usual combinations. Figure 65, page 75, is more complex with $a\{100\}$, $z\{111\}$, and $y\{122\}$ in addition to the above.

Topaz. $\breve{a}:\bar{b}:\dot{c} = 0.528:1:0.477$. Usual forms: $m\{110\}$, $l\{120\}$, $c\{001\}$, $f\{021\}$, $y\{041\}$, $u\{111\}$, $o\{221\}$, $i\{223\}$. Cleavage parallel to c. Interfacial

angles; $mm\{110:1\bar{1}0\} = 55° 43'$; $ll(120:\bar{1}20) = 86° 49'$; $ml(110:120) = 19° 44'$; $cf(001:021) = 43° 39'$; $cy(001:041) = 62° 21'$; $ci(001:223) = 34° 14'$; $cu(001:111) = 45° 35'$; $co(001:221) = 63° 54'$; $uu(111:1\bar{1}1) = 39° 0'$; $oo(221:2\bar{2}1) = 49° 38'$. Figures 199 to 202 represent usual types of topaz crystals. The lower part of these figures represents cleavage; doubly terminated crystals are very rare.

Graphic Determination of Indices and Axial Ratio in the Orthorhombic System. Figure 203 represents a barite in plan and side elevation. The unit faces are $m(110)$ and $u(101)$. What are

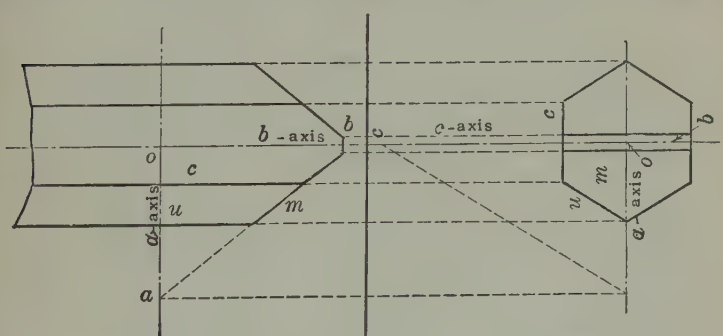


FIG. 203.—Plan and elevation of a barite crystal.

the axial ratios $\breve{a}:\bar{b}:\dot{c}$? The intercept of the m-face in the plan gives us oa, which is the unit length of the a-axis in terms of ob (the unit length on the b-axis). In the side elevation the line through a parallel to the u face determines the distance oc which is the unit-length of the c-axis in terms of ob of the plan.

7. THE MONOCLINIC SYSTEM

The monoclinic system includes all crystals in which there is a single direction fixed by symmetry not previously included (not A_3, A_4, or A_6). Three non-interchangeable axes of reference are used, one at right angles to the other two, which are in general inclined to each other. The axial elements are $\dot{a}:\bar{b}:\dot{c}$ and β, the angle between the a- and c-axes (see Fig. 204). In a few

cases β is equal to 90°. The unit length on the a-axis may be either shorter or longer than that on the b-axis which is taken as unity. The crystal is held so that the a-axis points down and toward the observer.

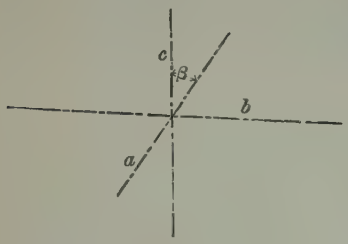


FIG. 204.—Monoclinic axes of reference.

Prismatic Class. $A_2 \cdot P \cdot C$

(Holohedral)

The axis of symmetry is normal to the plane of symmetry. The axis of 2-fold symmetry is the b-axis. The axes $\dot{a}$ and $\dot{c}$ are in the plane of symmetry, but their position is more or less arbitrary. They are usually taken parallel to prominent edges or faces.

Pinacoid	2 faces	{**001**}	(Basal pinacoid)
Pinacoid	2 faces	{**010**}	(Clinopinacoid)
Pinacoid	2 faces	{**100**}	(Orthopinacoid)
Pinacoids	2 faces	{**h0l**}, {$\bar{\mathbf{h}}$**0l**}	(Hemi-orthodomes)
Rhombic prism	4 faces	{**hk0**}	(Prism)
Rhombic prism	4 faces	{**0kl**}	(Clinodome)
Rhombic prisms	4 faces	{**hkl**}, {$\bar{\mathbf{h}}$**kl**}	(Hemi-pyramids)

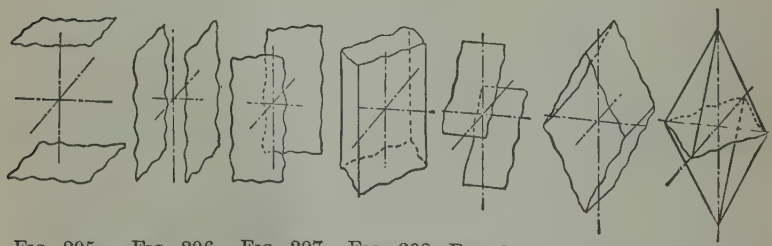


FIG. 205. FIG. 206. FIG. 207. FIG. 208. FIG. 209. FIG. 210. FIG. 211.
FIGS. 205–211.—The seven type forms in the prismatic class.

Pinacoid {001} (Basal pinacoid). This form is usually known as the basal pinacoid, but its faces are inclined and not perpendicular to the c-axis, Fig. 205.

Pinacoid {**010**} (Clinopinacoid). This may be called the *side pinacoid*, but it is also known as the clinopinacoid, Fig. 206.

Pinacoid {**100**} (Orthopinacoid). This form may be called the *front pinacoid*, but it is also known as the orthopinacoid, Fig. 207.

Rhombic Prism {**hk0**} (Prism). An open form consisting of four faces each parallel to the vertical axis, Fig. 208.

Rhombic Prism {**0kl**} (Clinodome). An open form consisting of four faces, each parallel to the a-axis. The a-axis is sometimes called the clino-axis hence the name clino-dome, Fig. 210.

Pinacoids {**h0l**}, {$\bar{\mathbf{h}}$**0l**}. (Hemi-orthodomes). These forms, each composed of two opposite parallel faces parallel to the b-axis (often called the ortho-axis), are independent of each other. Figure 209 represents $\{h0l\}$.

Rhombic Prisms {**hkl**}, {$\bar{\mathbf{h}}$**kl**} (Hemi-pyramids). These two forms occur independently, but together they constitute a figure that resembles a pyramid; hence the name *hemi-pyramid* is sometimes used. Figure 211 represents an $\{hkl\}$ form.

Combinations. All monoclinic crystals are necessarily combinations of two or more forms, as all the forms are open ones. As in the orthorhombic system, the habits are diversified. If the angle β is close to 90° there is often marked resemblance to orthorhombic crystals, but this result may also be due to equal development of front and back faces. Prismatic crystals are usually elongated in the direction of the c-axis, but occasionally in the direction of the b-axis, as in the case of epidote, and in the direction of the a-axis, as in orthoclase.

Examples

Many minerals and also artificially prepared substances crystallize in this class. Orthoclase ($KAlSi_3O_8$), diopside ($CaMgSi_2O_6$), augite ($R^{II}SiO_3$), and gypsum ($CaSO_4.2H_2O$) are given as good examples for study and practice. Microcline is triclinic, but is so close to the monoclinic in angles that it may readily pass for orthoclase.

Orthoclase. $\dot{a}:\bar{b}:\dot{c} = 0.658:1:0.555; \beta = 63° 57'$. Usual forms: $c\{001\}$, $b\{010\}$, $m\{110\}$, $z\{130\}$, $x\{\bar{1}01\}$, $y\{\bar{2}01\}$, $n\{021\}$, $o\{\bar{1}11\}$. Cleavage

parallel to c and b, also imperfect cleavage parallel to m. Interfacial angles: $mm(110:1\bar{1}0) = 61°\ 13'$; $bz(010:130) = 29°\ 24'$; $cx(001:\bar{1}01) = 50°\ 16'$; $cy(001:201) = 80°\ 18'$; ax(edge $1\bar{1}0, \bar{1}10:\bar{1}01$) $= 65°\ 47'$ [$a(\bar{1}00$ is a possible face truncating the edge $1\bar{1}0:\bar{1}10$]; $cn(001:021) = 44°\ 56'$; $bo(010:\bar{1}11) = 63°\ 8'$; $bc(010:001) = 90°\ 0'$; $cm(001:110) = 67°\ 47'$. Figures 212 to 215 represent usual types of crystals.

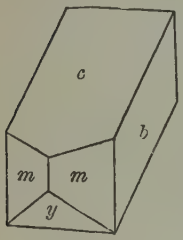


Fig. 212.

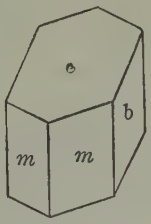


Fig. 213.

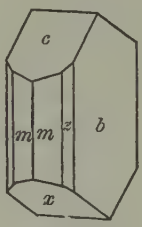


Fig. 214.

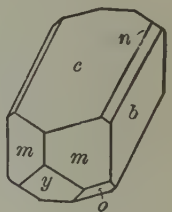


Fig. 215.

Figs. 212–215.—Orthoclase.

Diopside. $\dot{a}:\bar{b}:\dot{c} = 1.092:1:0.589$; $\beta = 74°\ 10'$. Usual forms: $c\{001\}$, $b\{010\}$, $a\{100\}$, $m\{110\}$, $p\{111\}$, $o\{\bar{2}21\}$, $d\{\bar{1}01\}$, $\Delta\{\bar{3}11\}$, $s\{\bar{1}11\}$. Interfacial angles: $mm(110:1\bar{1}0) = 92°\ 50'$; $ab(100:010) = 90°\ 0'$; $ac(100:001) = 74°\ 10'$; $bc(010:001) = 90°\ 0'$; $pp(111:1\bar{1}1) = 48°\ 29'$; $cp(001:111) = 33°\ 50'$; $ss(\bar{1}11:\bar{1}\bar{1}1) = 59°\ 11'$; $oo(\bar{2}21:\bar{2}\bar{2}1) = 84°\ 11'$; $\Delta\Delta(\bar{3}11:\bar{3}\bar{1}1) = 37°\ 50'$; $cd(001:\bar{1}01) = 31°\ 20'$. Figures 216–219 represent typical crystals of

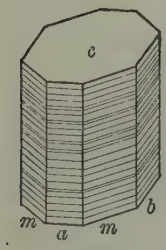


Fig. 216.

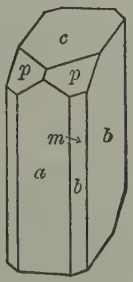


Fig. 217.

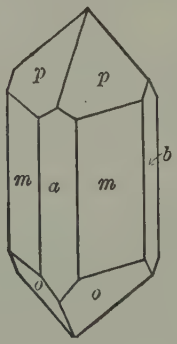


Fig. 218.

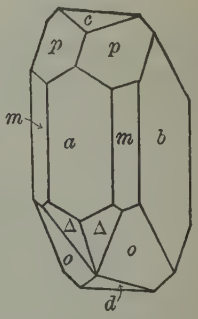


Fig. 219.

Figs. 216–219.—Diopside.

diopside. The striations on Fig. 216 are due to polysynthetic twinning with {001} as twin-plane.

Augite. Axial elements, usual forms, and interfacial angles practically the same as for diopside. Figures 220 to 223 represent the common types of augite crystals. Twins with {100} as twin-plane are common (see Fig. 223).

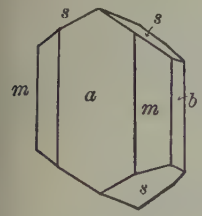


FIG. 220.

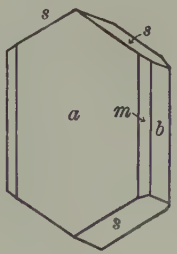


FIG. 221.

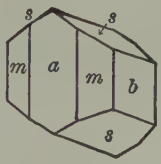


FIG. 222.

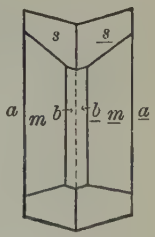


FIG. 223.

FIGS. 220–223.—Augite.

Gypsum. $\dot{a}:\bar{b}:\dot{c} = 0.690:1:0.412$; $\beta = 80° 42'$. Usual forms: $m\{110\}$, $l\{111\}$, $b\{010\}$, $n\{\bar{1}11\}$, $e\{\bar{1}03\}$. Cleavage parallel to b. Interfacial angles: $mm(110:1\bar{1}0) = 68° 30'$; $bm(010:110) = 55° 45'$; $ll(111:1\bar{1}1) = 36°$

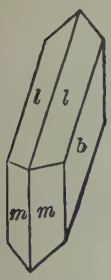


FIG. 224.

FIG. 225.

FIG. 226.

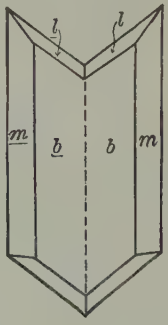


FIG. 227.

FIGS. 224–227.—Gypsum.

12′; $bn(010:\bar{1}11) = 69° 20'$; $bl(010:111) = 71° 54'$; $be(010:\bar{1}03) = 90° 0'$; ae(edge $1\bar{1}0,\bar{1}10:\bar{1}03) = 87° 49'$. The usual combination is bml, but with varying habit as represented in Figs. 224 and 225. Figure 227 represents a twin crystal with {100} as twin-plane.

Graphic Determination of Indices and Axial Elements in the Monoclinic System. An example of graphic determination is shown in Fig. 228, which is a plan and side elevation of an orthoclase (or microcline) crystal. The unit faces are $m(110)$ and $x(\bar{1}01)$; the problem is to determine the symbols of z and y and also the axial elements $\dot{a} : \bar{b} : \dot{c}$ and β. The a-axis is drawn parallel to $c(001)$ face (it appears foreshortened in the plan). A line is drawn from a in the plan parallel to the z-face. Its intersection on the b-axis determines the distance os, which is

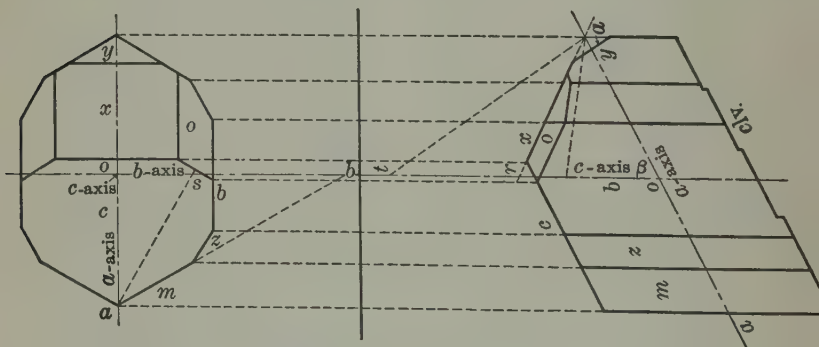


FIG. 228.—Plan and elevation of an orthoclase (or microcline) crystal.

$\frac{1}{3}ob$; hence the symbol of z is $1a : \frac{1}{3}b : \infty c$ which reduces to (130).

Similarly in the elevation, a line through $-a$ parallel to y intersects the c-axis at the point, t. As the distance $ot = 2\,or$ (or is the intercept of the unit face x) the symbol of y is $-1a : \infty b : 2c$ or $(\bar{2}01)$. The symbol of o proves to be $\bar{1}11$ for it is common to the two zones $[010 : \bar{1}01]$ and $[001 : \bar{1}10]$.

The distance oa (in the elevation) is the unit length of the a-axis in terms of ob in the plan (the b-axis), and the distance or in the elevation is the unit length of the c-axis in terms of ob also.

14. THE TRICLINIC SYSTEM

The triclinic system includes all crystals in which there are no directions fixed by symmetry. The axes of reference are three non-interchangeable axes, in general at oblique angles, which are taken parallel to three prominent edges. The axial elements are $\breve{a} : \bar{b} : \dot{c}$ (the unit on $\bar{b}$ being unity, and the unit on $\breve{a}$ usually less than unity) and the angles α, β, and γ between the axes $\bar{b}$ and $\dot{c}$, $\breve{a}$ and $\dot{c}$, $\breve{a}$ and $\bar{b}$ respectively. Figure 229 represents a possible triclinic axial cross.

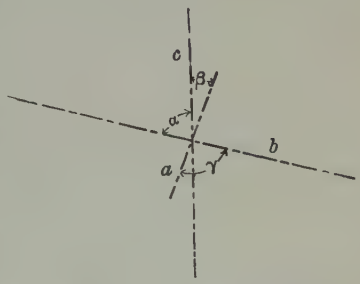


FIG. 229.—Triclinic axes of reference.

The triclinic system includes two classes, one with a center of symmetry and the other without any symmetry whatever. As no known mineral is devoid of symmetry, only the pinacoidal class is considered here.

Pinacoidal Class. C

(Holohedral)

The choice of axes is arbitrary, but they are usually taken parallel to the intersection edges of the three most prominent faces. In some cases, as in the triclinic feldspars, directions corresponding to those in the monoclinic feldspar, orthoclase, are chosen.

List of Forms in the Pinacoidal Class

Pinacoid	2 faces	{001}	(Basal pinacoid)
Pinacoid	2 faces	{010}	(Brachypinacoid)
Pinacoid	2 faces	{100}	(Macropinacoid)
Pinacoids	2 faces	{hk0}, {$h\bar{k}$0}	(Hemi-prisms)
Pinacoids	2 faces	{0kl}, {0$\bar{k}$l}	(Hemi-brachydomes)
Pinacoids	2 faces	{h0l}, {$\bar{h}$0l}	(Hemi-macrodomes)
Pinacoids	2 faces	{hkl}, {$\bar{h}$kl}, {$h\bar{k}$l}, {$\bar{h}\bar{k}$l}	(Tetarto-pyramids)

All forms are pinacoids each of which consists of two opposite parallel faces.

Combinations. The appearance of triclinic crystals depends largely upon the obliquity of the axes. Many of them closely approach monoclinic crystals in angles. This is especially the case with the plagioclase feldspars.

Examples

Comparatively few minerals crystallize in this class. The only common ones are the plagioclase feldspars, rhodonite, kyanite, and microcline. Albite ($NaAlSi_3O_8$) is selected as the best mineral for study. Albite crystals are usually so small that measurements must be made by the reflection gonometer. Microcline is triclinic but is so close to orthoclase in angles that it may pass for monoclinic. (The optical properties, especially the oblique extinction on the 001 cleavage face, prove that it is triclinic.)

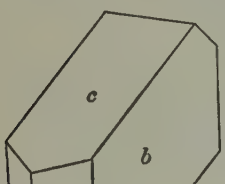


FIG. 230.—Albite.

Albite. $\breve{a}:\breve{b}:\breve{c} = 0.633:1:0.556$; $\alpha = 93°\ 58'$; $\beta = 63°\ 39'$; $\gamma = 87°\ 31'$. Usual forms: $m\{1\bar{1}0\}$, $M\{1\bar{1}0\}$, $c\{001\}$, $b\{010\}$, $x\{\bar{1}01\}$, $y\{\bar{2}01\}$, $f\{130\}$, $z\{1\bar{3}0\}$, $n\{021\}$, $p\{\bar{1}11\}$, $o\{\bar{1}\bar{1}1\}$. Cleavage parallel to c and b. Interfacial angles: $mM(110:1\bar{1}0) = 59°\ 16\frac{1}{2}'$; $mf(1\bar{1}0:1\bar{3}0) = 30°\ 24'$, $Mz(110:130) = 29°\ 36'$; $mb(110:010) = 60°\ 58'$; $cx(001:\bar{1}01) = 52°\ 6\frac{1}{2}'$; $cy(001:201) = 81°\ 53'$; Figure 230 represents an albite crystal with the forms: $c\{001\}$, $b\{010\}$, $m\{110\}$ $M\{1\bar{1}0\}$ and $x\{\bar{1}01\}$.

Graphic Determination of the Indices in the Triclinic System. Figure 231 shows a plan and side elevation of an albite crystal. The unit faces are $m(110)$, $M(1\bar{1}0)$, and $x(\bar{1}01)$; the problem is to determine the symbols of f, z, y, and p. ($c = 001$; $b = 010$). The determinations are made just as they were in the case of Fig. 228; the only difference is that the b-axis is not normal to the $b(010)$ face. The following symbols are obtained $f = (130)$; $z = (1\bar{3}0)$; $y = (\bar{2}01)$; $p = (\bar{1}11)$.

15. COMPOSITE CRYSTALS AND CRYSTALLINE AGGREGATES

Loose, isolated crystals are comparatively rare in nature. They usually occur in groups. The grouping may be in parallel

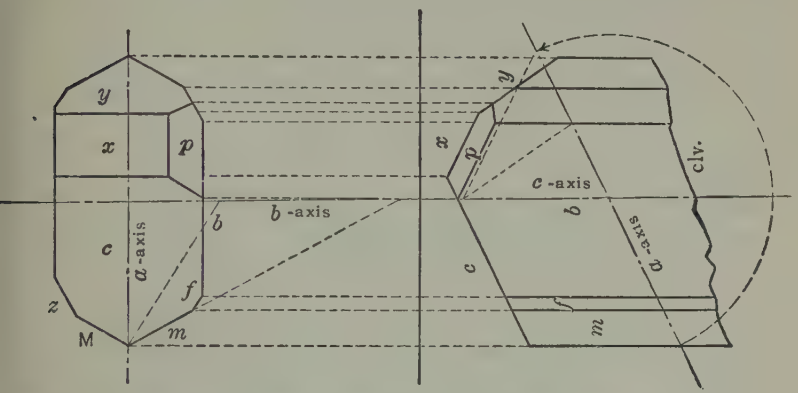


FIG. 231.—Plan and elevation of an albite crystal.

position (see Fig. 232), in the most irregular manner, or in the third condition of partial parallelism.

Twinning

The peculiar sort of grouping in partial parallelism is known as **twinning**; crystals so grouped are called **twin-crystals.** Many crystals are found to be composed of two parts, one half of which *apparently* has been revolved 180° about a line called the **twin-axis.** These may be called **rotation twins.** Other crystals have two portions symmetrically placed with reference to a plane called the **twin-plane.** These may be called **reflection twins.** In a third type the two individuals are symmetrical to a point, though neither of the crystals has a center of symmetry. These are called **in-**

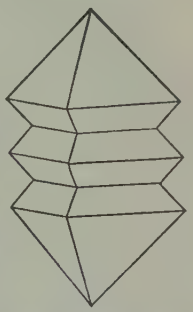


FIG. 232.—Octahedra in parallel position.

version twins. The face of union of the two individuals is called the **composition-face.** It may or may not be the twin-plane. The twin-plane is always a crystal face or a possible crystal face, but never a plane of symmetry. The twin-axis is always

Fig. 233. Contact twin.

Fig. 234. Penetration twin.

Fig. 235. Cyclic twin.

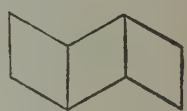


Fig. 236. Polysynthetic twin.

Figs. 233–236.

a possible crystal edge or a line normal to a possible crystal face, but it is never a 2-fold, 4-fold, or 6-fold axis of symmetry. Two general types of twin-crystals are distinguished: (1) **contact twins** with a definite composition face and (2) **penetration twins** with an indefinite or irregular composition face. Figure 233 is a diagrammatic representation of a contact twin and Fig. 234, that of a penetration twin. In the case of contact twins the **twin-law** is defined with respect to a twin-plane, while in penetration twins it is defined with respect to a twin-axis.

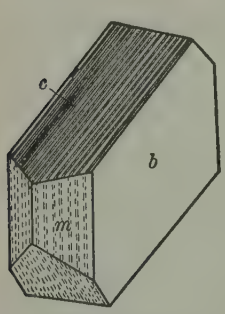


Fig. 237.—Plagioclase.

In addition to twins composed of two individuals, there are also multiple twins made up of three or more parts. If the same face serves as twin-plane for a series of individuals we have a **polysynthetic twin** (Fig. 236). But if different faces (of the same form) are twin-planes we have a **cyclic twin** (Fig. 235).

A polysynthetic twin may consist of a large number of individuals and some of these may be so narrow that they appear

as striations. Cleavages of calcite and of plagioclase often show **twinning striations.** In calcite, the rhombohedron $\{01\bar{1}2\}$ is the twin-plane, and so on the cleavage face $\{10\bar{1}1\}$ the striations are parallel to the long diagonal as represented in Fig. 251. In plagioclase the twin-plane is usually $b\{010\}$, and so the twin striations appear on the $c\{001\}$ cleavage face as narrow bands parallel to the (001:010) edge as shown in Fig. 237.

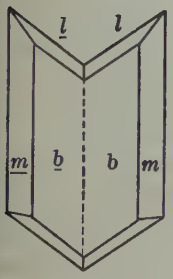


Fig. 238.
Gypsum.

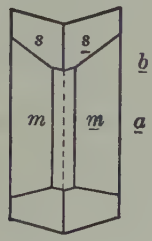


Fig. 239.
Augite.

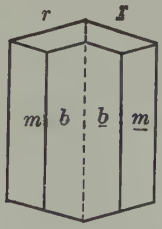


Fig. 240.
Hornblende.

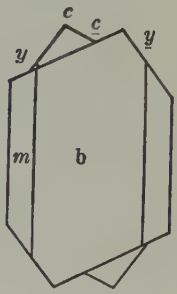


Fig. 241.
Orthoclase.

Examples

Figure 238 represents a twin of gypsum with $\{100\}$ as twinning plane. In Figs. 239 (augite) and 240 (hornblende), $\{100\}$ is also twin-plane. Figure 241 represents a Carlsbad twin of orthoclase. This is a penetration twin with the c-axis as twin-axis.

Figure 242 represents a cruciform penetration twin of staurolite. In Fig. 243 a contact twin of aragonite with $m\{110\}$ as twin-plane is shown. A penetration trilling of cerussite is illustrated by Fig. 244. Figure 245, a twin of marcasite, apparently has an axis of 5-fold symmetry. The angles in this case would be exactly 72° (⅕ of 360°), but accurate measurement proves four of them to be 74° 55′ instead.

Figures 246 to 249, inclusive, represent various kinds of rutile twins, but in each case (101) is the twin-plane. Figure 246 is a simple contact twin; Fig. 247 shows twin striations. A single band inserted in twinning position like Fig. 248 is called **a twin-seam.** Figure 249 is a cyclic twin. These four figures are orthographic parallel projections made on the (100) plane.

The next row of figures illustrates four of the five twin-laws known for calcite. Figure 250 is the scalenohedron $\{21\bar{3}1\}$ twinned on $\{0001\}$. Figure 251 represents a calcite cleavage with twin lamellæ inserted parallel to $\{01\bar{1}2\}$, which is the most

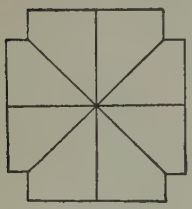


Fig. 242. Staurolite.

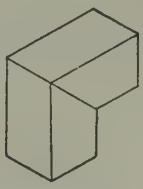


Fig. 243. Aragonite.

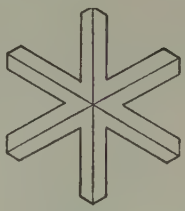


Fig. 244. Cerussite.

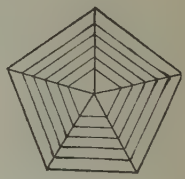


Fig. 245. Marcasite.

common twin-law for calcite. Figure 252 is a calcite twin with $\{10\bar{1}1\}$ as twin-law, while Fig. 253 is a scalenohedron twinned on $\{02\bar{2}1\}$, one of the rare twin-laws for calcite.

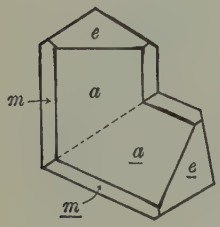


Fig. 246.

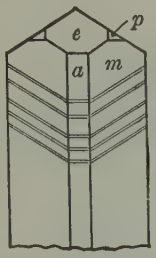


Fig. 247.

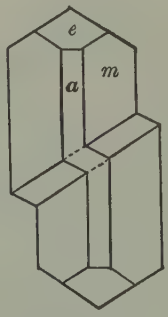


Fig. 248.

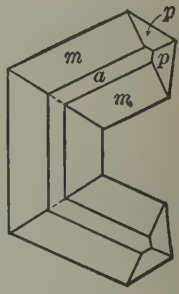


Fig. 249.

Figs. 246–249.—Rutile.

The next four figures represent twins of the isometric system. Figure 254 (with 111 as twin-plane) is called the spinel twin because it is so common for the mineral spinel. Figure 255 represents twin striations observed on cubic cleavages of galena. Here

the twin-plane is the trisoctahedron {441}. A penetration twin of fluorite with the cube diagonal as twin-axis is represented in Fig. 256, while Fig. 257 is a twin of pyrite with the *a*-axis as twin-axis. This twin is known as the "iron cross."

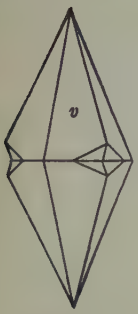


FIG. 250.

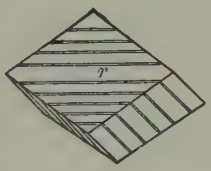


FIG. 251.

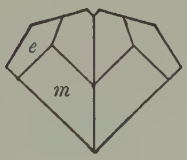


FIG. 252.

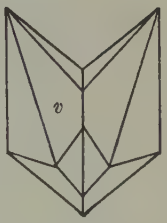


FIG. 253.

FIGS. 250–253.—Calcite.

Many apparently simple crystals are in reality twins. In such cases optical tests are usually necessary to reveal their composite character.

Twins are usually recognized by the presence of reëntrant angles, but there are exceptions to this general rule, as for example, hornblende, Fig. 240, p. 125.

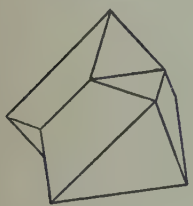


FIG. 254. Spinel.

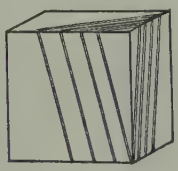


FIG. 255. Galena.

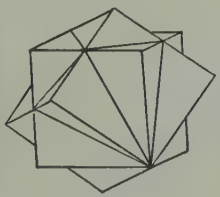


FIG. 256. Fluorite.

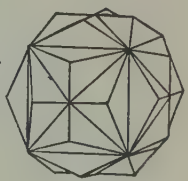


FIG. 257. Pyrite.

The tendency of twinning is to raise the grade of symmetry apparently. This is especially the case with pseudo-hexagonal orthorhombic minerals such as aragonite, witherite, and cerussite. See Figs. 472, 473, 474, and 478.

Crystalline Aggregates

Most minerals consist of crystal aggregates which do not possess definite crystal faces. That such minerals are crystalline, however, may be determined by certain physical properties, particularly the optical properties. The kinds of crystalline aggregates are distinguished by certain terms which are constantly used in the description of minerals.

A mineral made up of plates is called **lamellar** (example, *barite*). If the layers are readily separated the term **micaceous** is used (example, *hematite*). An aggregate of more or less parallel imperfect crystals is called **columnar** (example, *aragonite*); and the same on a smaller scale is **fibrous** (example, *gypsum*). Fibrous radiating aggregates of crystals are known as **spherulites** (example, *chalcedony*). A flat columnar aggregate is said to be **bladed** (example, *kyanite*). The term **granular** needs no explanation (example, *magnetite*).

The forms assumed by many aggregates derive their names from some natural object. **Nodular** is the term used for irregular rounded lumps (example, *pyrite*). **Mammillary** refers to low rounded prominences (example, *smithsonite*). **Botryoidal** is from a Greek word meaning a bunch of grapes (example, *chalcedony*). **Reniform** means kidney-shaped (example, *hematite*). The last three terms are so closely related that it is often difficult to decide which term to use. The term **colloform** was proposed several years ago by the author for the more or less spherical forms assumed by amorphous and metacolloid minerals in free spaces. **Pisolitic** is the term used for an aggregate of shot-like masses (example, *cliachite*), while **oölitic** is similar except that the spheres are smaller, about like fish-roe (example, *calcite*). **Stalactitic** indicates that the mineral is found in icicle-like forms (example, *calcite*). **Dendritic** means branching like a tree (example, *copper*). **Concretions** are more or less spherical masses formed by the tendency of matter to gather around a center (example, *siderite*). A **geode** is a hollow concretion usually lined with

crystals (example, *quartz*.) A **vug** is a cavity in a rock or vein lined with crystals.

16. CLEAVAGE AND PARTING

Many crystals have the property of breaking with smooth surfaces in certain directions which are parallel either to actual

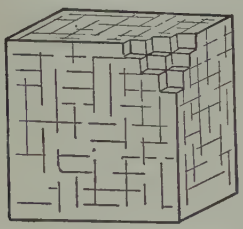


FIG. 258.—Cubic cleavage.

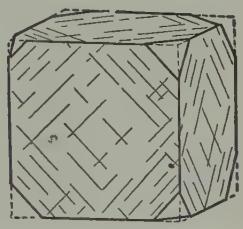


FIG. 259.—Octahedral cleavage.

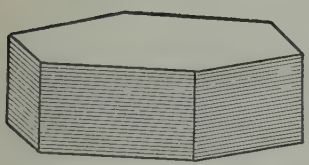


FIG. 260.—Mica cleavage.

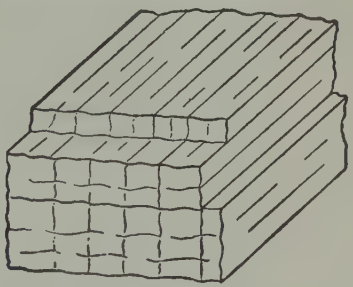


FIG. 261.—Feldspar cleavage.

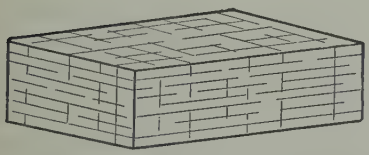


FIG. 262.—Barite cleavage.

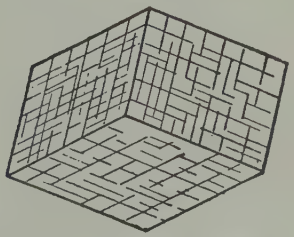


FIG. 263.—Calcite cleavage.

or possible crystal faces. This important property is known as **cleavage.** (It really belongs among the physical properties but

is so intimately related to the crystal form that it is discussed here.) Galena, which usually crystallizes in cubes, has a cubic cleavage (Fig. 258), while fluorite, which also crystallizes in cubes, has an octahedral cleavage (Fig. 259). (The octahedron is a form sometimes found on fluorite). Cleavage is defined according to the direction as cubic, rhombohedral, prismatic, etc., and according to the character of the surface, such terms as imperfect, good, perfect, and very perfect being used. Thus the micas have a very perfect cleavage parallel to (001) (Fig. 260), while the feldspars have a perfect cleavage parallel to (001) and good cleavage parallel to (010) (Fig. 261).

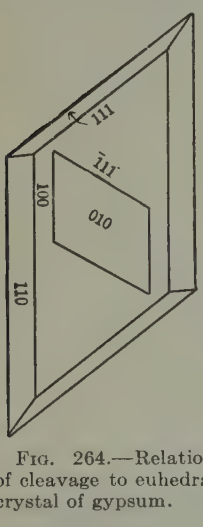


Fig. 264.—Relation of cleavage to euhedral crystal of gypsum.

In barite, an orthorhombic mineral, the cleavage is perfect in one direction parallel to (001), and a little less perfect in two directions parallel to (110) (Fig. 262). In gypsum there is a very perfect cleavage parallel to (010), an imperfect cleavage with conchoidal surface parallel to (100), and an imperfect cleavage with fibrous surface parallel to ($\bar{1}11$). The relation of a cleavage fragment of gypsum to a crystal is shown in Fig. 264. Here the inner rhombic figure is the result of cleavage. A line normal to the paper is an axis of twofold symmetry for the cleavage fragment, as well as for the crystal. But, in general, cleavage shows a greater degree of symmetry than crystal form for the simple reason that the presence or absence of a center of symmetry cannot be established by cleavage alone. For example, tetrahedral cleavage cannot be distinguished from octahedral cleavage. In calcite, whatever the shape of the crystal, the cleavage is perfect rhombohedral in three directions at angles of 74° 55′ to each other. Figure 263 represents a cleavage of calcite with three surfaces and intersecting cleavage traces on each.

Cleavage is a fairly constant property of minerals, and is

invaluable in the rapid recognition of minerals. Such minerals as calcite, fluorite, feldspars, amphiboles, and gypsum are distinguished principally by their cleavage.

On the other hand, such minerals as quartz and garnet possess practically no cleavage. They break with an irregular **fracture.** In chalcedony the fracture is conchoidal (curved like the interior of a shell). Other terms applied to fracture such as splintery, hackly, even, and uneven are self-explanatory.

The term **parting** is applied to a separation due to some molecular disturbance, such as twinning. Cleavage may be obtained in any part of a crystal in the given direction; the size and the number of the cleavage particles are limited

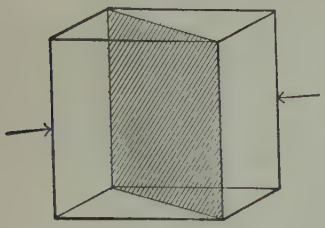


FIG. 265.—Halite parting.

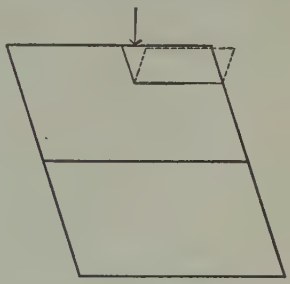


FIG. 266.—Calcite parting.

only by the mechanical appliance available. Parting, on the other hand, takes place only along certain definite planes, those of the molecular disturbance. In a cubic cleavage of rock-salt, if pressure is applied in a direction normal to a vertical diagonal plane, a surface normal to the direction of pressure is developed, (the shaded plane in Fig. 265). In this case we have an example of dodecahedral parting. If pressure is applied by a dull knife edge normal to the obtuse edge of a cleavage rhombohedron of calcite, a small portion of the calcite will be reversed in position, forming a twin with $(01\bar{1}2)$ as twinning plane. This phenomenon is known as **gliding.** In this case the small portion of calcite in Fig. 266 may be easily removed; the parting is par-

allel to $(01\bar{1}2)$, a plane normal to the direction of the pressure and is produced by **secondary twinning.** In ice, gliding may take place in a direction normal to the *c*-axis (ice crystallizes in the hexagonal system). This may explain in part the movement of glaciers.

One case is known in which the direction of parting is not a possible crystallographic plane. Some cleavage pieces of plagioclase show well-defined parting almost, but not quite, parallel to {001} See Fig. 267. This parting is due to pericline twinning, a method of twinning in which the *b*-axis is the twin-axis. In the triclinic system, if the *b*-axis is a twin-axis, the composition face of a twin is not a possible crystal face.

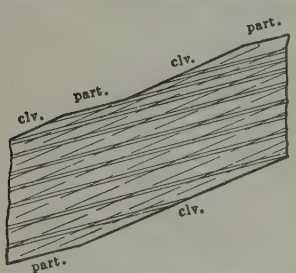


FIG. 267.—Pericline parting in plagioclase.

Prominent examples of parting are the following: basal parting (001) in diopside (Fig. 216, page 118), basal parting (001) in stibnite, octahedral parting (111) in magnetite, and rhombohedral parting $(01\bar{1}2)$ in calcite.

17. THE INTERNAL STRUCTURE OF CRYSTALS

The law of simple rational indices is the foundation stone of geometrical crystallography. In addition to the formulation of the law given on page 74 it may be stated in another way. If from a point, lines parallel to the intersection edges of three prominent non-parallel faces of a crystal be drawn, and a plane parallel to a fourth chosen face also be drawn there may be constructed from the four points *O*, *A*, *B*, *C* (Fig. 268) thus established, a series of parallelopipeds of indefinite extent with *OAGBECDF* as a unit cell. Such a network of points constitutes a **space-lattice.** The particular one shown in Fig. 268 is triclinic, the distances *OA*, *OB*, and *OC* are unequal, and the angles between them oblique. Besides the four planes mentioned, many others may be drawn by connecting any three points of the space-lattice.

Now the possible faces of a crystal are parallel to the possible planes of the space-lattice. This is a geometrical expression of the law of rational indices without any theory whatever as to the internal structure of crystals.

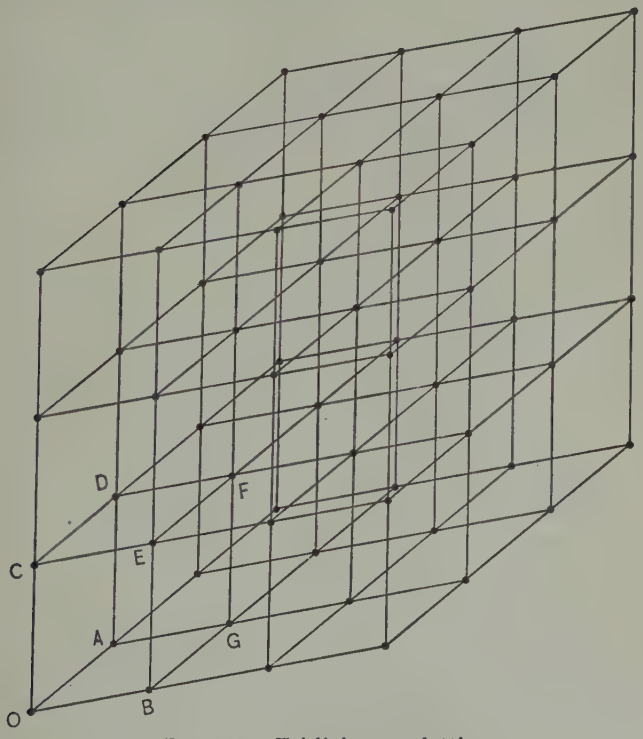


FIG. 268.—Triclinic space-lattice.

A point to be considered is the limitation of the term "simple" in the expression "law of simple rational indices." All the planes possible within the limits of Fig. 268 are those with simple indices, but it is clear that possible planes of the lattice may be represented by as large numbers as we choose if the lattice is sufficiently extended. Now what are the actual facts? We find that the

crystal faces of common occurrence are those with simple indices: 0, 1, 2, 3, 4, 5, and 6, rarely above 10. For example, if we take the {*hhl*} faces of all orthorhombic minerals (97 in number), we find that those with 4 as the highest index occur on 16 different minerals, those with 6 as the highest index occur on 5 different minerals, those with 7 as the highest on 3 minerals, and those with 9 as the highest on 2 minerals. Forms such as {9.9.10}, {12.12.11}, and {5.5.19} occur on only one mineral. Geometrically expressed, the faces of most frequent occurrence are those of the greatest reticular density. This is shown by Fig. 269 which

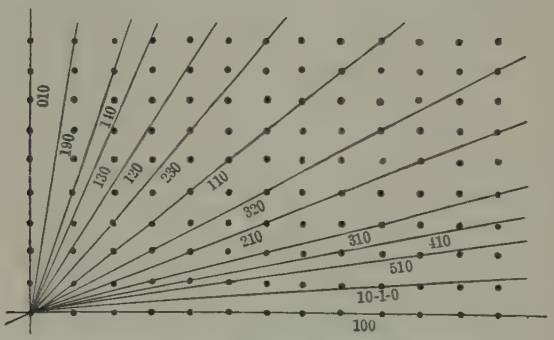


FIG. 269.—Diagram showing the reticular density of {hk0} faces in an orthorhombic crystal.

may be taken to represent some of the possible *hk*0 forms in the orthorhombic system. This fact, which is independent of any theory, is known as the **law of Bravais.**

Whether a crystal actually possesses a space-lattice or not is another question. In 1905, Friedel, a French crystallographer, formulated the **law of rationality of symmetric intercepts** (see page 74), which added to the law of rationality of indices practically proved the existence of the space-lattice. Direct proof, however, was not furnished until the work of Laue in 1912.

The problem of crystal structure resolves itself into two more or less independent questions: (1) the nature of the constituent

particles of the crystal and (2) their arrangement in space. The second problem is essentially a mathematical one. It is simply necessary to find all the possible arrangements of points in space, for the constituent particles, whatever their nature, may be represented by points.

All the possible space-lattices belong to one of seven types of symmetry *viz.*: **C, A_2·P·C, $3A_2$·3P·C, A_4·$4A_2$·5P·C, $A_3(\not P_6)$·$3A_2$.-3P·C, A_6·$6A_2$·7P·C,** and **$3A_4$·$4A_3(4\not P_6)$·$6A_2$·9P·C.** It will be noted that the only symmetry axes present are those with periods

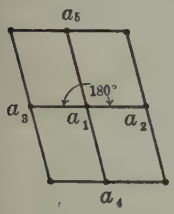


Fig. 270.

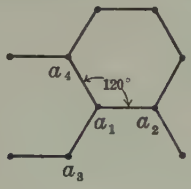


Fig. 271.

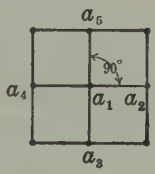


Fig. 272.

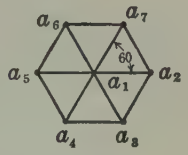


Fig. 273.

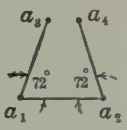


Fig. 274.

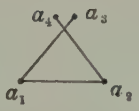


Fig. 275.

Figs. 270–275.—Diagrams showing possible axes of symmetry in a space-lattice.

of 2, 3, 4, and 6, and the fact that only these axes of symmetry have been found on crystals makes it probable, apart from any other considerations, that crystals have a regular internal structure. The diagrams of Figs. 270–275 will make it clear that only these symmetry axes are possible in a space-lattice. Let a_1, a_2, a_3, etc. represent the points of a space-lattice and the projection of the lines of the space-lattice. Let a_1a_2 be the smallest possible distance between them (the distances are not infinitesimal). Rotation around symmetry axes of 180°, 120°, 90°, and 60° respectively will then give us the points a_3 in Fig. 270, a_3 and a_4

in Fig. 271, a_3, a_4, and a_5 in Fig. 272, and a_3, a_4, a_5, a_6 and a_7 in Fig. 273. These figures show that axes of 2-, 3-, 4-, and 6-fold symmetry are possible.

Next take the case of a 5-fold axis of symmetry. In Fig. 274 a rotation of 72° ($\frac{1}{5}$ of 360°) about a_1 brings a_2 to a_3, and a similar rotation about a_2 brings a_1 to a_4. But a_3a_4 is smaller than the original distance a_1a_2, which is contrary to hypothesis. Therefore an axis of 5-fold symmetry is impossible. If, in a similar way, we take an angle of rotation less than 60° (Fig. 275), the new points a_3 and a_4 result, but the distance a_3a_4 is also smaller than the original distance, a_1a_2. Therefore axes of n-fold symmetry with n greater than 6 are impossible.

The first substantial contribution to the subject of crystal structure was made by Bravais, a French physicist in 1850. He found that fourteen space-lattices are possible. They include in addition to the seven primary lattices enumerated below.

Primary Space-lattices	Other Space-lattices
Cubic (Fig. 276)	Centered cube (Fig. 277)
Hexagonal prism (Fig. 281)	Face-centered cube (Fig. 278)
Rhombohedron (Fig. 282)	Centered square prism (Fig. 280)
Square prism (Fig. 279)	Centered rectangular prism (Fig. 286)
Rectangular prism (Fig. 285)	Rhombic prism (Fig. 283)
Monoclinic parallelopiped (Fig. 288)	Centered rhombic prism (Fig. 284)
Triclinic parallelopiped (Fig. 289)	Clinorhombic prism (Fig. 287)

seven others which may be derived by combining two lattices in a symmetrical manner. For example, the centered square prism (Fig. 280) is made up of two interpenetrant square prism lattices, one derived from the other by shifting it in the direction of its diagonal for a distance equal to one-half of its diagonal. This operation is known as **translation.** Now the fourteen space-lattices of Bravais are the only possible ones that may be obtained by adding translations to the symmetry-operations, provided no translations less than one-half the distance between the points of a primary lattice are used. Every Bravais space-lattice necessarily has a center of symmetry.

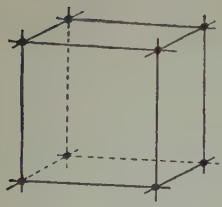


FIG. 276.

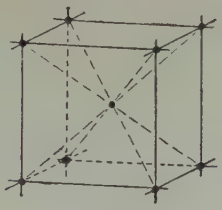


FIG. 277.

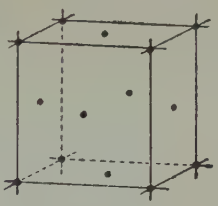


FIG. 278.

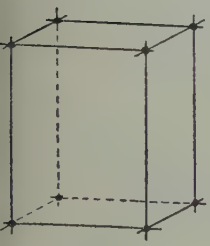


FIG. 279.

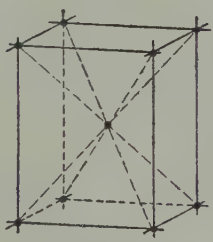


FIG. 280.

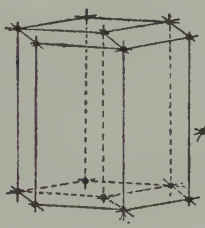


FIG. 281.

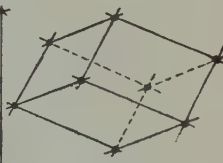


FIG. 282.

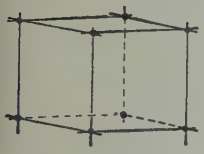


FIG. 283.

FIG. 284.

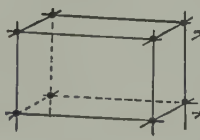


FIG. 285.

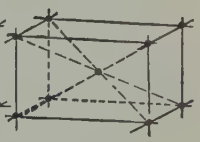


FIG. 286.

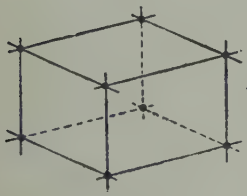


FIG. 287.

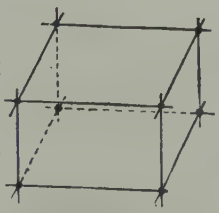


FIG. 288.

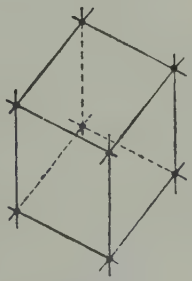


FIG. 289.

FIGS. 276–289.—The fourteen space-lattices of Bravais.

Sohncke in 1879 discovered a new kind of symmetry operation applicable to points in space, *viz.*, a **screw-axis of symmetry,** which is an axis around which a spiral movement takes place. It may be produced by combining an ordinary axis of symmetry with a translation along the direction of the axis. An example of a 4-fold screw-axis of symmetry is shown in Fig. 290. The point b may be derived from a, c from b, d from c, a_1 from d, and so on, by a clockwise rotation of 90° combined with a translation t, equal to $\frac{1}{4}\ aa_1$. A screw-axis may be either right-handed or

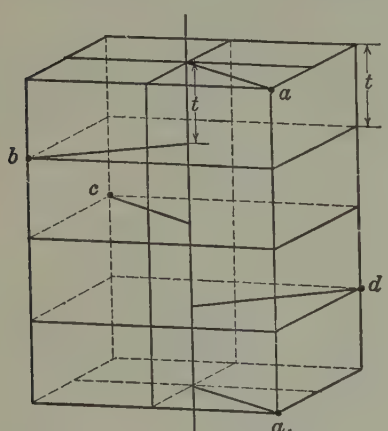


Fig. 290.—Screw-axis of symmetry.

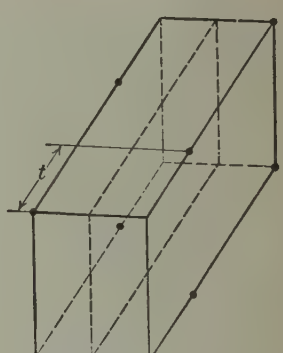


Fig. 291.—Glide-plane of symmetry.

left-handed; it is thus possible to account for exactly similar, but enantimorphous, crystals such as those of quartz (see Figs. 420–21, p. 260). By adding screw-axes to the 14 Bravais space-lattices, Sohncke proved that 57 kinds of arrangements of points are possible. These are called **point-systems.**

It was soon realized that Sohncke's work was incomplete, and the Russian crystallographer Fedorov a little later found that a new type of symmetry was necessary, **viz. a glide-plane of symmetry,** which is the result of combining reflection in a plane of symmetry with a translation parallel to the plane. An

example is shown in Fig. 291. The dotted lines are the traces of a glide-plane of symmetry, for with a translation equal to t, this plane becomes a plane of symmetry. (A tessellated pavement furnishes a good example in two-dimensional space). The result of combining translations, screw-axes, and glide-planes with the ordinary symmetry-operations of finite figures furnished Fedorov (1890) with 230 possible kinds of **space-groups**. Each of these space-groups belongs to one of the 32 point-groups. Schoenflies (1891) and Barlow (1894) arrived at the same conclusion independently. The mathematical side of the problem of crystal structure was thus firmly established, and Friedel's recognition of the law of the rationality of symmetric intercepts in 1905 practically proved that a space-lattice exists in crystals.

Visible proof of the space-lattice, however, was not forthcoming until 1912. The results obtained in the next few years have opened up one of the most interesting fields in the whole realm of science.

The first experimental work on crystal structure originated in an attempt to determine the nature of X-rays. It was doubtful whether X-rays consisted of a wave-motion or were material in nature. Laue, a Swiss physicist, conceived the idea that a crystal might act as a 3-dimensional diffraction grating for X-rays if the latter consisted of a wave-motion. In order to test this, a beam of X-rays was directed upon a crystal plate of sphalerite (isometric ZnS), and a photograph was obtained which showed a central circular spot surrounded by elliptical spots of varying intensity arranged in a symmetrical manner. Two radiograms (X-ray photographs) of sphalerite are shown in Figs. 292a and 292b. Fig. 292a was taken from a crystal plate cut parallel to a cube face and Fig. 292b from a plate cut parallel to a tetrahedral face.

The experiment had succeeded and proof was furnished that the mysterious X-rays discovered by Roentgen are the result of a wave-motion similar to, but with much shorter wave-length than, that of light. The central spot of the photograph is pro-

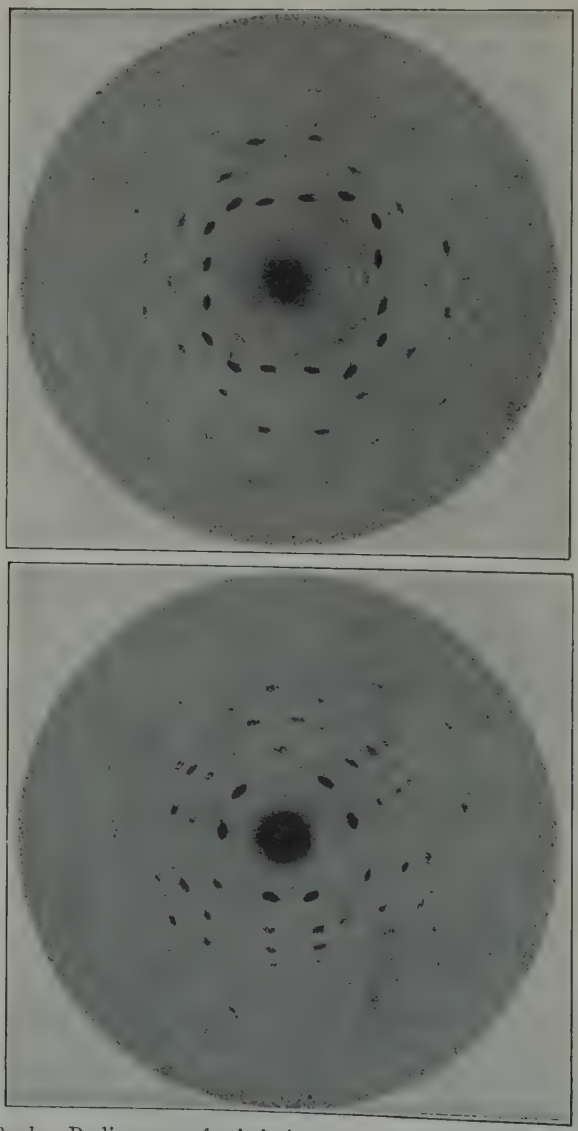


FIG. 292*a*-*b*.—Radiograms of sphalerite (after Frederich and Knipping).

duced by the direct beam of X-rays and the other spots are due to secondary beams produced by reflections from internal planes of particles. (The actual particles are of course too small to show separately, for millions of them are present even in a minute crystal.) The fact that the intensity of the spots is proportional to the reticular density of the plane just as the relative frequency of occurrence of crystal forms makes it possible to determine the actual position of the constituent particles.

This work has been undertaken by a number of investigators, notably the English physicist, W. H. Bragg, and his son, W. L. Bragg. The Braggs introduced a method different from that of Laue. They mounted the crystal upon an X-ray

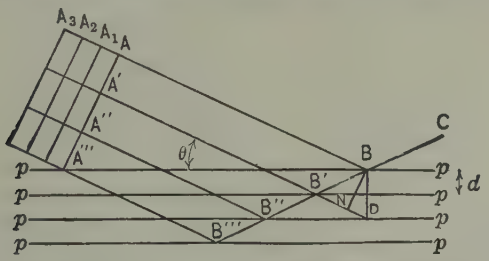


Fig. 293.—Explanation of X-ray diffraction effects (after the Braggs).

spectrometer, an instrument in which the telescope of the ordinary spectrometer is replaced by an ionisation chamber, and used a beam of X-rays of given wave-length analogous to a beam of monochromatic light. (In the Laue experiments the general radiation corresponding to white light was used.) As the mounted crystal is revolved about the axis of the spectrometer, effects are obtained over a considerable range of angles. At certain angles the leaf of the electroscope attachment moves and the intensity of the movement may be read off on a suitable scale. The reason that the leaf of the electroscope moves only at certain angles may be shown by a consideration of Fig. 293. The horizontal lines *pp*, etc., represent traces of internal planes in the crystal with the spacing d. A, A_1, A_2, A_3. . . . are a train of

X-ray waves of wave length λ. (It is to be noted that d and λ are of the same order of magnitude which makes it possible to use a crystal as an X-ray diffraction grating.) The reflected wave BC is the result of reflections from successive planes B, B', B'', B''', etc., provided the distance ND is equal to λ or a multiple of λ, for then all the trains of reflected waves are in the same phase and the intensity is equal to the sum of their amplitudes. If the distance ND is not equal to λ or $n\lambda$ there is no reflection. It is clear then that reflection takes place only at certain angles $\lambda = 2d \sin \theta_1$; $2\lambda = 2d \sin \theta_2$; $3\lambda = 2d \sin \theta_3$; etc. ($ND = 2d \sin \theta$). For a different crystal face the value d will be different and consequently the angle θ. The readings obtained can then be used to interpret the crystal structure. The results obtained by the Braggs for sphalerite are shown in Fig. 294 for the three important faces of the isometric system *viz.*, the cube {100}, the dodecahedron {110}, and the octahedron {111}. For the octahedral or tetrahedral plane there are four readings, corresponding to spectra of the first, second, third, and fourth order of the diffraction grating. Now there are three different kinds of space-lattice possible in the isometric system: (1) the cube (Fig. 276), the centered cube (Fig. 277), and the face-centered cube (Fig. 278). The distance of adjacent reticular planes in the three cases for the prominent faces are as follows:

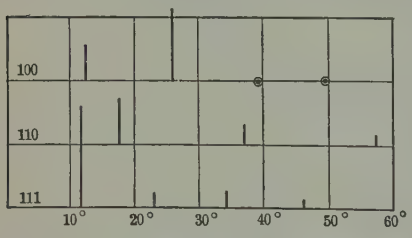


FIG. 294.—X-ray spectrometer readings for sphalerite (after the Braggs).

Cube lattice $\frac{1}{d_{(100)}} : \frac{1}{d_{(110)}} : \frac{1}{d_{(111)}} :: 1 : \sqrt{2} : \sqrt{3}$

Centered cube lattice $\frac{1}{d_{(100)}} : \frac{1}{d_{(110)}} : \frac{1}{d_{(111)}} :: 1 : \frac{1}{\sqrt{2}} : \sqrt{3}$

Face-centered cube lattice $\frac{1}{d_{(100)}} : \frac{1}{d_{(110)}} : \frac{1}{d_{(111)}} :: 1 : \sqrt{2} : \sqrt{\frac{8}{2}}$

The ratios of the sines of the angles for sphalerite given in Fig. 294 are practically as $1:\sqrt{2}:\sqrt{\frac{3}{2}}$, which proves that the constituent particles of a sphalerite crystal lie at the points of a face-centered cubic lattice. The Braggs conclude that equally spaced planes parallel to the cube contain Zn and S atoms alternately (Fig. 295), that equally spaced planes parallel to the dodecahedron contain both Zn and S atoms (Fig. 296), and that unequally spaced planes parallel to the octahedron (or tetrahedron) contain Zn and S atoms alternately, also that the Zn–Zn distance is four times the Zn–S distance (Fig. 297). The internal structure of sphalerite must then be that shown in Fig. 298. (The lines of the figure are of course imaginary. They are

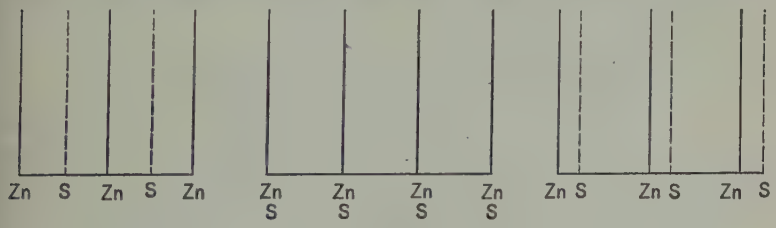


FIG. 295. FIG. 296. FIG. 297.

FIGS. 295–297.—Spacing of planes of atoms in sphalerite (after the Braggs).

drawn simply to show the relation of the atoms to each other). The zinc atoms lie on a face-centered cubic lattice and the sulfur atoms on another face-centered cubic lattice distant one-fourth of the diagonal of the cube apart. The symmetry elements of the structure are as follows: There are dodecahedral planes of symmetry through the Zn and S atoms at intervals of $\frac{1}{4}\sqrt{2}a$, where a is the dimension of the edge of the unit cube, and halfway between these, glide-planes of symmetry with a translation of $\frac{1}{2}\sqrt{\frac{3}{2}}\ a$ in the direction between the central Zn and the lower front right Zn. Lines normal to the cube planes at the projection of all the zinc and sulfur atoms are composite planes and four-fold axes of symmetry with the planes at intervals of $\frac{1}{2}a$. There are also two-fold screw-axes of symmetry with translation of $\frac{1}{2}a$

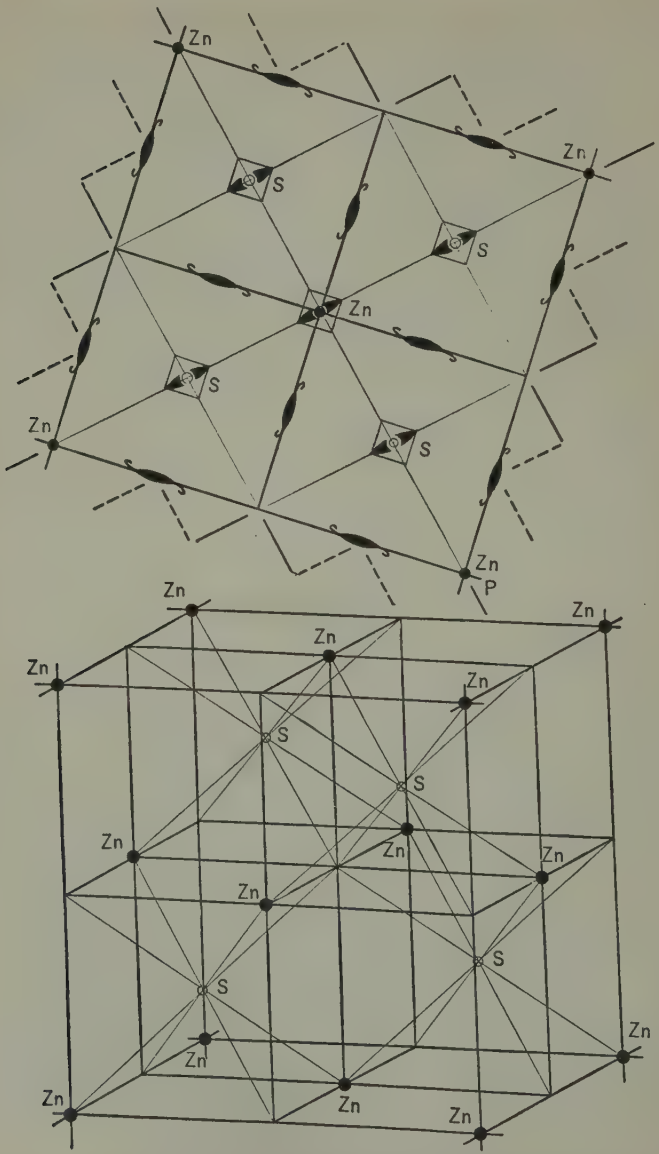


FIG. 298.—The internal structure of sphalerite.

along vertical and horizontal lines half-way between vertical and horizontal lines of Zn-atoms. No centers of symmetry are present for the three-fold axes of symmetry lying along the cube diagonals are polar. The space-lattice shown in Fig. 298 thus accounts for the symmetry of sphalerite: $4A_3 \cdot 3A_2(3\not{P}_4) \cdot 6P$.

The Laue radiogram of Fig. 292*a* apparently shows four planes of symmetry (axial as well as diagonal) intersecting in a central axis of 4-fold symmetry but Friedel has proved that a radiogram does not tell us whether a center of symmetry is present or not.

The unit cube of the sphalerite structure contains 4 sulfur atoms and 4 zinc atoms, for the zinc atoms at the 8 corners each belong equally well to the seven adjacent cubes and each of those at the centers of the cube faces belong equally well to an adjacent cube. $[(8 \times \frac{1}{8}) + (6 \times \frac{1}{2}) = 4]$. This does not mean that the molecular formula of sphalerite is 4 ZnS for it is probable that the molecule does not exist in crystalline solids, but only in gases, liquids, and amorphous solids.

The structure of diamond is similar to that of sphalerite except that all the points of Fig. 298 are carbon atoms. The dodecahedral planes are planes of symmetry with intervals of $\frac{1}{4}\sqrt{2}a$ and the cube planes at intervals of $\frac{1}{4}a$ are glide-planes of symmetry with translation of $\frac{1}{2}a$ along a line normal to a cube edge. Composite four-fold axes of symmetry are at the projections of all the carbon atoms and corresponding to the two-fold screw-axes of Fig. 298 we have instead, four-fold screw-axes with translations of $\frac{1}{4}a$ in the direction of the cube edges. The three-fold axes of symmetry are no longer polar as in the case of sphalerite. The work of the Braggs proves that diamond belongs to the hexoctahedral or holosymmetric class of the isometric system.

In practically all of the discussions of crystal structure the idea of a unit is prominent. The term "particle" often is used instead of molecule because of the possibility that the unit of structure is a collection of molecules instead of a single molecule. Some interpret the *X*-ray work of the Braggs to mean that molecules as such do not exist in crystals, but in the opinion of

others this conclusion is premature. The molecule, if such exists, may escape detection by *X*-ray methods. In any event the *X*-ray experiments prove that not only the units of structure but also the individual atoms are arranged in space-lattices which was predicted by Groth in 1905. The sphalerite crystal of Fig. 298, for example, is built up of two interpenetrant space-lattices, one of Zn atoms and the other of S atoms. The nature of the unit of crystal structure still remains in doubt.

The *X*-ray analysis of crystals combined with a mathematical study of the possible arrangements of points in space has furnished us with a means of determining the stereochemistry of the solid or crystalline state and has thus thrown new light on the structure of matter. This work also promises to be of value in settling many doubtful questions concerning crystals. It has truly opened up one of the most interesting fields in the whole realm of science.

THE PHYSICAL PROPERTIES OF MINERALS

Two classes of physical properties are recognized. Physical properties such as specific gravity are independent of the direction and are called **scalar** properties, while others, such as cohesion and the effect of light, heat, and electricity, can be represented by a line of given length and direction, hence the term **vectorial** properties.

Vectorial properties may be divided into two general groups: continuous and discontinuous. Properties that can be represented by a smooth curve such as the curve of hardness (Fig. 299), are **continuous vectorial properties,** and those that vary discontinuously such as etch-figures (Fig. 300) are **discontinuous vectorial properties.** The following is a tabulation of some of the prominent physical properties.

Scalar Properties
- Specific Gravity
- Specific Heat

Vectorial Properties

Continuous
- Hardness
- Elasticity
- Ellipsoidal Properties: Optical, p. 156; Thermal; Magnetic; Electr c

Discontinuous
- Cleavage, p. 129
- Etching, p. 66

The discontinuous vectorial properties, cleavage and etching, are so closely related to the morphological properties that they have been described under that heading rather than under the physical properties.

Of all the continuous vectorial properties the optical properties

are the most important from both the theoretical and practical standpoints and for that reason they are treated in a separate division.

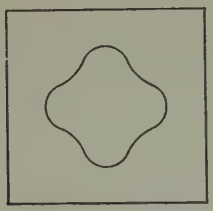


FIG. 299.—Curve of hardness on cube face of fluorite.

FIG. 300.—Etch-figure on cube face of fluorite.

1. SPECIFIC GRAVITY

The density of a substance compared with the density of water under standard conditions (4°C.) is called the **specific gravity.** A specific gravity of 3 means that the substance weighs three times as much as an equal volume of water. The specific gravity is the weight of a substance divided by the weight of an equal volume of water. Five methods of finding the specific gravity are described.

(*a*) A rough, but rapid, method is to weigh out a gram of the mineral and then find its volume with a burette. Care must be taken to eliminate air-bubbles. If one gram is used, the specific gravity is the reciprocal of the volume.

(*b*) A more accurate method is based on the fact that a body immersed in water loses in weight an amount equal to the weight of the water displaced. The substance has the weight A in air, say. Suspended by a fine thread in a vessel of water, it has the weight W. Then $G = \frac{A}{A-W}$, where G is the specific gravity. Numerous precautions must be taken to insure accuracy.

(*c*) A **convenient specific gravity balance** for the practical identification of minerals is that represented in Fig. 301, which was designed by the author. It consists essentially of a brass

beam supported near one end by a knife edge. The short arm carries two pans; the lower one is immersed in water. The end of the long arm rests within a guard, which limits the motion of the balance. The long arm of the beam is graduated so that the specific gravity may be read off directly. This may be done by always placing the counterpoise in the notch near the end of the long arm when weighing in air. Whatever the weight of the counterpoise, its distance (x) from the fulcrum and the distance (y) of the counterpoise from the fulcrum when weighing in water are connected by the equation, $G = \frac{x}{x - y}$, G being the specific gravity. The distance y for various values of G is de-

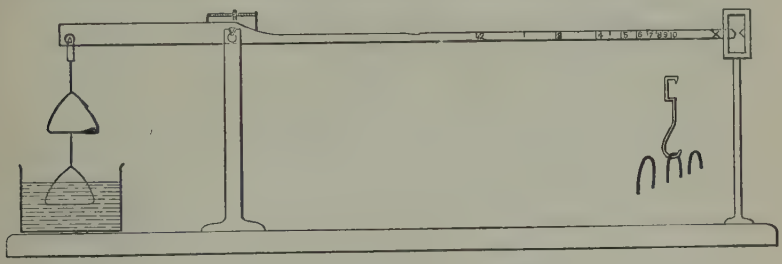


FIG. 301.—Specific gravity balance.

termined and the corresponding value for G is marked on the beam. Thus in the balance figured, x is 15 inches. Then if G is 2, y is 7.5; so 2 is marked at a point 7.5 inches from the fulcrum. If G is 3, y is 10; so 3 is marked at a point 10 inches from the fulcrum. The balance is adjusted by a device just above the fulcrum. When in adjustment the balance will look like the figure, the lower pan being immersed in water and the long arm of the balance free. The mineral is placed on the upper pan and the counterpoise in the notch near the end of the long arm. Wire loops are added to the hook of the counterpoise until the mineral is balanced. Then the mineral is transferred to the lower pan. (It is well to moisten the mineral before immersion so as to free it of air bubbles.) The mineral will lose weight, so

the counterpoise is moved toward the fulcrum until balance is restored. *The specific gravity is indicated directly on the beam.* This method is rapid, and the results are accurate enough for the practical purposes of determination.

(*d*) For accurate work a pycnometer or specific gravity flask may be used. The pycnometer itself is first weighed (*A*). The coarsely powdered mineral is introduced into the pycnometer and another weighing (*B*) made. The flask is then filled with distilled water, and air bubbles are eliminated by boiling. After cooling, the weight (*C*) is taken. Then the flask is emptied and filled with distilled water, weight (*D*). Then $G = \frac{B - A}{D + B - A - C}$. With proper precautions this method is very accurate. Fibrous or porous minerals should be finely powdered, otherwise the value is too low.

(*e*) A number of heavy liquids are useful in determining the specific gravity. Methylene iodid (CH_2I_2) has a specific gravity of 3.3 and may be diluted with benzol (sp. gr. = 0.98); this forms a liquid with any desired intermediate specific gravity. A water solution of potassium mercuric iodid ($KI.HgI_2$), also called Thoulét solution, has a specific gravity of 3.19 and may be mixed with water in any proportion. The specific gravity of a mineral may be determined by diluting these liquids until fragments of the mineral neither sink nor float, but remain suspended. A Westphal balance is then used to determine the specific gravity of the liquid. The heavy liquids are especially useful in separating mixtures of minerals for the purpose of analysis.

The specific gravities of the common and important minerals are given below.

MINERALS ARRANGED ACCORDING TO SPECIFIC GRAVITY

1.0	1.7	Sylvite
Ice	1.8	2.1
1.6	1.9	Chabazite
Carnallite	2.0	CHRYSOCOLLA
Ulexite	SULFUR	GRAPHITE

HALITE
Hydromagnesite
Kainite
OPAL
Stilbite

2.2
Analcite
Chalcanthite
Chrysotile
Cristobalite
Halloysite
Heulandite
Natrolite

2.3
Apophyllite
Glauconite
Tridymite
GYPSUM
Nitratine
Sodalite

2.4
Brucite
Colemanite
Gibbsite
Lazurite

2.5
ANTIGORITE
CLIACHITE
Garnierite
Leucite

2.6
Adularia
Albite
Alunite
CHALCEDONY
Kaolinite
Microcline
ORTHOCLASE
Nepheline
Oligoclase
QUARTZ
PLAGIOCLASE
Scapolite
Vivianite

2.7
Andesine
Anorthite
Beryl
Bytownite
CALCITE
Labradorite
PLAGIOCLASE
Scapolite
TALC
Turquois

2.8
CHLORITE
COLLOPHANE
DOLOMITE
Lepidolite
MUSCOVITE
Pyrophyllite
Phlogopite
Sericite
Wollastonite

2.9
ANHYDRITE
Aragonite
BIOTITE
Datolite
Prehnite

3.0
Cryolite
Dahllite
Tremolite

3.1
Andalusite
Anthophyllite
Chondrodite
Glaucophane
Magnesite
Spodumene
TOURMALINE

3.2
APATITE
Diopside
FLUORITE
Forsterite
Jarosite
HORNBLENDE
PYROXENE
Sillimanite

3.3
Augite
Axinite
Clinozoisite
Enstatite
OLIVINE

3.4
CALAMINE
EPIDOTE
Hypersthene
Vesuvianite

3.5
Diamond
Rhodochrosite
Titanite
Topaz

3.6
GARNET
Kyanite
Rhodonite
Spinel

3.7
Staurolite
Strontianite

3.8
Azurite
GARNET
LIMONITE
PSILOMELANE
SIDERITE

3.9
Brochantite
Celestite
MALACHITE

4.0
CORUNDUM
GARNET
PSILOMELANE
SPHALERITE
4.1
Carnotite
Turyite
Willemite
4.2
CHALCOPYRITE
PSILOMELANE
Rutile
4.3
Goethite
Manganite
Turyite
Witherite
4.4
CHROMITE
Enargite
SMITHSONITE
4.5
BARITE
STIBNITE
Turyite
4.6
Covellite
PYRRHOTITE
Zircon
4.7
Ilmenite
Molybdenite
TETRAHEDRITE
Turyite
4.8
Hausmannite
Pentlandite
Pyrolusite
4.9
Marcasite
5.0
PYRITE
5.1
BORNITE
Franklinite
MAGNETITE
5.2
HEMATITE
Stibiconite
5.3
5.4
5.5
Cerargyrite
5.6
Columbite
5.7
CHALCOCITE
Jamesonite
5.8
Pyrargyrite
5.9
Columbite
6.0
ARSENOPYRITE
Cuprite
Scheelite
6.1
Polybasite
6.2
Columbite
Smaltite
Stephanite
6.3
Anglesite
6.4
Bismuthinite
6.5
CERUSSITE
6.6
6.7
Wulfenite
6.8
Pyromorphite
Vanadinite
6.9
7.0
CASSITERITE
Pitchblende
7.1
7.2
Mimetite
7.3
Argentite
7.4
Wolframite
7.5
GALENA
Iron
Pitchblende
8.0
CINNABAR
Pitchblende
8.8
Calaverite
COPPER
10.5
SILVER
15 to 19
GOLD
Platinum

2. HARDNESS

The resistance that a substance offers to abrasion is called hardness. It is not a property that is capable of exact definition

or measurement, but comparative tests are expressed in terms of a so-called **scale of hardness.** The scale of hardness consists of ten minerals ranging from talc, a mineral which has a soapy feel and is very easily scratched by the finger nail, up to diamond, the hardest known substance. The scale of hardness is as follows:

Scale of Hardness

1 Talc
2 Gypsum
Finger Nail
3 Calcite
4 Fluorite
5 Apatite
Knife Blade
6 Orthoclase
7 Quartz
8 Topaz
9 Corundum
10 Diamond

The finger nail is about $2\frac{1}{2}$, for it scratches gypsum, but is scratched by calcite. A knife blade is about $5\frac{1}{2}$, for it scratches apatite, but is scratched by orthoclase. The hardness of a mineral is judged both by its effect on the minerals of the scale and their effect upon it. If a mineral scratches fluorite but is scratched by apatite, it has a hardness of $4\frac{1}{2}$. Two minerals of the same hardness will scratch each other.

Great care should be used in determining the hardness. A foreign substance embedded in the mineral will often give too high a value. A soft mineral leaves a "chalk-mark" on a harder one, so the mark left by a mineral should be a distinct groove. Minerals made up of grains or fibers often appear too low simply because the particles are forced apart. Thus a sandstone made up of sand grains with hardness of 7 may appear to have a hardness of about 3 simply because the grains are loosely cemented. The value recorded in the description of minerals is the maximum value for well-crystallized varieties.

In crystals the hardness varies with the direction, as do practically all the physical properties except specific gravity. This is shown in Fig. 299, p. 148. The amount of abrasion of the crystal is determined for a number of directions by mounting the crystal on an instrument known as a **sclerometer.** The values are plotted and connected by a smooth curve known as the **curve of hardness.** The most remarkable case of variation of the hardness with direction is probably that of kyanite (triclinic Al_2SiO_5). Kyanite in a direction parallel to the *c*-axis has a hardness of 4½, while at right angles to this the hardness is about 7. For most faces calcite has a hardness of 3, but on the basal pinacoid (0001) the hardness is about 2, as this face is easily scratched by the finger nail.

3. LUSTER

Luster is the term applied to the quality of light reflected from a substance. **Metallic luster** is the brilliant luster of metals possessed by most sulfid minerals such as galena, pyrite, etc., as well as some oxids such as hematite and magnetite. Minerals with metallic luster are opaque even on the thinnest edges.

Adamantine is the brilliant luster of transparent or translucent minerals with high index of refraction. Examples are diamond ($n = 2.41$) and cerussite ($n = 1.80 - 2.07$). **Vitreous** is the luster of broken glass possessed by most transparent or translucent minerals such as quartz, calcite, etc. **Pearly** luster is due to continued reflection from a series of parallel plates, and is possessed by minerals with eminent cleavage such as gypsum and talc. **Silky** luster is due to fibrous structure and is illustrated by chrysotile and fibrous gypsum. Waxy, greasy, pitchy, and dull are self-explanatory terms used to describe luster.

4. COLOR

The term **color** is a general one, and for convenience usually includes black (which really means the absence of color) and white (the union of all colors). The solar spectrum is the standard for

non-metallic colors. The term **hue** refers to a particular part of the spectrum. Thus we speak of an orange hue or a green hue. A given spectrum hue illuminated (or mixed with white) becomes a **tint,** while a given hue with insufficient illumination (or mixed with black) becomes a **shade.** Thus pink is a tint of red, and olive green a shade of yellow. Besides tints and shades produced from the spectrum we have other colors formed by mixing the spectrum hues with various grays (mixtures of black and white).

In some minerals such as cinnabar, orpiment, malachite, and azurite the color is a property of the substance and hence is constant. The color of a metallic mineral is usually quite constant, but as these minerals are susceptible to tarnish a fresh fracture should always be observed.

But in the majority of non-metallic minerals the color is due to some impurity which usually exists in very small amounts, and is often present as a pigment in solid solution. Thus quartz, calcite, and fluorite are colorless when pure, but they are found in various tints and shades of practically all hues which may vary even in the same specimen.

5. STREAK

The **streak** of a mineral refers to the color of its powder. It may be determined by rubbing a corner of the mineral on a piece of unglazed porcelain or tile called a **streak-plate.** In the absence of a streak-plate a smooth piece of light colored flint or chert may be used. A thin slab of novaculite also makes an excellent streak-plate.

The streak, though colorless for most non-metallic minerals and dark-gray or black for many metallic ones, is especially valuable in the determination of a few common minerals such as hematite (streak, red-brown) and limonite (streak, yellow-brown).

THE OPTICAL PROPERTIES OF MINERALS

Among the physical properties, the optical properties take first rank in the accurate description and determination of all minerals that transmit light in thin layers, for the mineral may be determined even in the absence of distinct crystals and when occurring in small quantities.

Most of the optical determinations can be made by means of a special form of microscope known as the polarizing microscope, but for the more accurate determination of the optical constants the refractometer, the goniometer, and the axial angle apparatus must be used.

Minerals for optical determinations may be prepared in three different forms: (1) oriented sections or sections cut in definite crystallographic directions, (2) thin sections in which the constituent minerals are cut at random (by this means minerals in fine grained rocks may be determined), and (3) fragments, cleavage flakes, and minute crystals. As fragments are easily prepared simply by crushing the mineral, the method is a general one for the examination of all but opaque minerals. *The polarizing microscope should have a place in the mineralogical laboratory and should supplement the blowpipe in the determination of minerals.* It is safe to say that, generally speaking, it is impossible to determine the less common non-metallic minerals without the use of the polarizing microscope.

1. THE NATURE OF LIGHT

It is now generally believed that light consists of a vibratory motion or some kind of disturbance in the ether, a hypothetical medium which is supposed to pervade all space and even material bodies.[1] The **wave-motion,** as it is called, is regarded as the

[1] Light is a form of energy and as we can not conceive of energy being transmitted without some kind of medium, physicists postulate a something different from ordinary matter which they call the ether.

resultant of simple harmonic motion and a uniform linear motion at right angles to this. Simple harmonic motion is uniform motion in a circular path as it would appear on a diameter of the circle. The circle of reference, as it is called, is shown in Fig. 302 (*adgj*). A point moving from *a* to *d* appears to move from *a'* to *d*. This constitutes a periodic vibration with varying velocity which may be represented by the swinging of a pendulum. If this is compounded with linear motion from A to A', we have the harmonic curve ADGJA', which is a sine curve represented by the equation $y = a \sin \frac{2\pi}{T} x$, in which *a* is OD, the amplitude

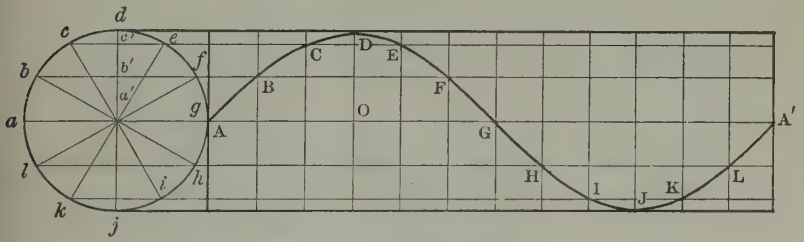


FIG. 302.—Wave-motion.

and $\frac{2\pi}{T}$, the angular velocity in the circle. Fig. 302 illustrates the wave-motion at a given instant.

Thus light consists, to the best of our knowledge, of a periodic vibration transverse to the direction of transmission, though we know nothing of its physical nature. It may be illustrated in a rough way by the waves observed along the sea-shore. A floating object, in general, simply moves up and down, while the wave as a whole advances toward the shore.

The maximum displacement, OD (Fig. 302), is called the **amplitude** of the vibration. The **period** is the interval of time necessary for a complete vibration. The point with the maximum upward displacement, D, is called the crest of the wave and the point with maximum downward displacement, J, the trough.

The distance between two successive crests or troughs, or a corresponding distance such as AA′, is called the **wave-length** (denoted by the Greek letter λ [lambda]). The number of vibrations executed in a unit of time defines the **frequency.**

By **phase** is meant the relative position of any two points. Two points such as A and A′ are in the **same phase** when they are in the same relative position and moving in the same direction. Two points such as A and G are said to be in **opposite phase** when they are in the same relative position but moving in opposite directions.

A **ray** of light is a line used to indicate the direction of transmission of the wave-motion, but in practice beams of light must be employed. A **wave-front** is the surface determined by all the parts of a system of waves which are in the same phase. A ray is perpendicular to its wave-front in an optically isotropic medium.

The intensity of light depends upon the amplitude of the vibrations, and the color of the light depends upon the wave-length of the vibrations or, more accurately, upon the frequency, for the wave-length is altered when the light enters any material medium. The wave-length for the violet end of the spectrum is 380$\mu\mu$ (millimicrons or millionths of a millimeter) and for the red end of the spectrum, 760$\mu\mu$ (millionths of a millimeter). White light is the sum of light of the various waves which together produce the solar spectrum. For this reason **monochromatic light** (light of approximately one wave-length) must be employed in all accurate optical work. The simplest method of obtaining monochromatic light is to ignite a sodium salt on platinum wire in a dark room. Yellow light with a wave-length of 589$\mu\mu$ is produced. For red light a lithium salt is used and for green light a thallium salt. In the laboratory it is more convenient to use a colored screen which gives light with a considerable range of wave-lengths, but for quantitative work strictly monochromatic light must be used.

2. REFRACTION OF LIGHT

When a beam of light passes from one medium into another, in general there is a change of direction, which is due to the fact that there is a change of velocity in the light waves. This is shown in Fig. 303. Parallel rays pp' on passing from air, say, into a section, arrive at the points rr' together. But while the impulse along the ray p' is going the distance $r's'$ in the air, that along the ray p has gone the distance rs, the velocity in the section being less than in air. The wave-front in the section is then ss' constructed by drawing a line from s' tangent to an arc with radius rs (rs being the velocity in the action as compared with velocity $r's'$ in air). The beam of light is bent toward the perpendicular. This phenomenon is known as **refraction.** A familiar illustration is the apparent bending of a stick in water. In Fig. 304 the angle i is called the *angle of incidence*, and the angle r, the *angle of refraction*. The radii of the two concentric circles are proportional to the indices of refraction of the two substances (air and a liquid in this case). The value of r for any given value of i may be found by extending the incident ray until it cuts the smaller concentric circle. From this intersection a perpendicular is dropped to the bounding surface of the two media. A line drawn from the intersection of this perpendicular with the larger circle to the center gives the direction of the refracted ray. There is found to be a constant relation between the sines of these angles, for whatever the direction of transmission, $\frac{\sin i}{\sin r} = n$ (a constant). The constant n, which is called the **index of refraction,** depends upon the substance and upon the kind of monochromatic light used. The index of refraction for the violet end of the spectrum is greater than for the red end of

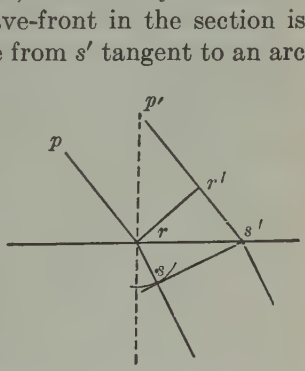


FIG. 303.—The relation of velocity to index of refraction.

the spectrum as shown in Fig. 305. For diamond the dispersion or difference between the values of the refractive indices for opposite ends of the spectrum is very large ($n_v - n_r = 0.063$), hence the "fire" of the diamond. For fluorite, on the other hand, the dispersion is very small ($n_v - n_r = 0.006$), hence fluorite

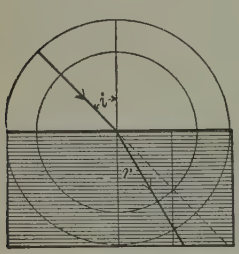


Fig. 304.

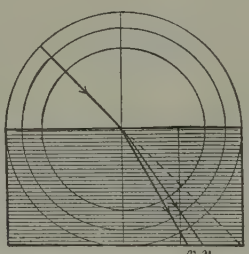


Fig. 305.

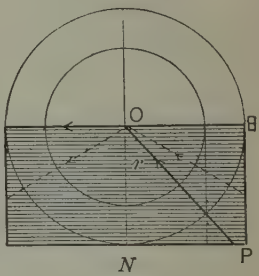


Fig. 306.

is often used in making achromatic microscope lenses. The following list gives the indices of refraction (yellow light) for some of the common minerals:

Fluorite	1.434
Gypsum	1.520–1.529
Quartz	1.544–1.553
Barite	1.636–1.647
Apatite	1.635–1.638
Corundum	1.759–1.767
Cerussite	1.804–2.078
Sphalerite	2.369

The minerals in the above list with the exception of fluorite and sphalerite are doubly refracting and so the index of refraction ranges from a minimum to a maximum depending upon the direction of the light rays.

Substances with a high index of refraction (1.9 or over) have the brilliant appearance called adamantine luster, minerals with an index of refraction lower than 1.7 have ordinary vitreous luster, while those between 1.7 and 1.9 (*e.g.* corundum) have subadamantine luster.

Several particular directions of transmission should be mentioned. In the formula $\frac{\sin i}{\sin r} = n$, if $i = 0°, r = 0°$; so for normal incidence there is no refraction. If $i = 90°$, the equation becomes $\sin r = \frac{1}{n}$; r for this particular value is called the **critical angle.** The critical angle like the index of refraction is a constant for the substance. A graphic determination of this angle is shown in Fig. 306. The indices of refraction of the two substances are the radii of two concentric circles, AB being the boundary between the two substances. A tangent is dropped from the intersection of the inner circle with the boundary line. A radius is then drawn through the point where this tangent intersects the outer circle. The angle PON is the critical angle.

Rays of light passing from the denser (lower) medium to the rarer (upper) medium along the line PO will graze the surface OA. Rays of light passing from the denser into the rarer medium at angles greater than the critical angle cannot enter the rarer medium, but are reflected back into the denser medium as illustrated by the dotted line of Fig. 306. This phenomenon is called **total reflection.** An empty test-tube immersed in a beaker of water has a peculiar silvery appearance caused by total reflection. This silvery reflection disappears when the test-tube is filled with water. The reason for the silvery appearance may be shown by constructing the critical angle for water and air on a drawing of the test-tube in a beaker of water.

The great brilliancy of the cut diamond, as compared with natural crystals of the uncut diamond, is due principally to the fact that the facets are arranged so that most of the light is totally reflected, for the critical angle for diamond is very small (24° as compared with 48° for ordinary glass).

Direct Determination of the Index of Refraction

The index of refraction is the fundamental optical constant, and its determination is one of the best means of identifying a given

mineral or other substance, provided of course that it transmits light.

The most direct procedure for determining the index of refraction is called the **prism method.** The crystal cut in the form of a prism of about 60° (internal angle) is mounted on a reflection goniometer or spectrometer. A narrow beam of light from the collimator is refracted both on entering and emerging from the prism, as shown diagrammatically in Fig. 307. If the prism

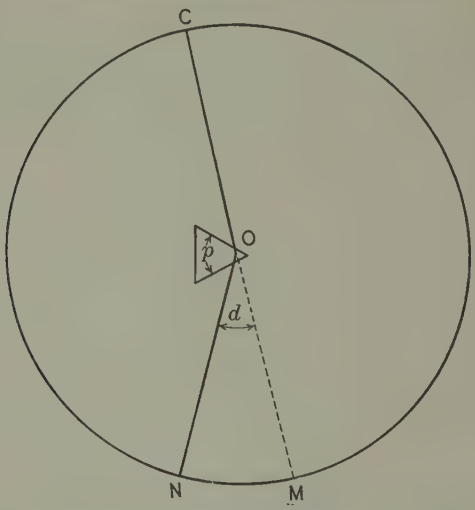


FIG. 307.—Determination of index of refraction by the prism method.

were not present the beam of light, CO, would reach the point M but instead it is deviated out of its course and reaches a point such as N. The direct reading with the telescope at M is taken and then the telescope is moved to the left. The crystal is then revolved on the axis of the goniometer until the refracted image is in the field of view. The crystal and telescope are then manipulated, one with each hand, until the image first moves in one direction and directly afterwards in the opposite direction. This momentary and stationary position of the image determines the

angle of minimum deviation, d, from which the index of refraction may be calculated by the equation $n = \frac{\sin \frac{1}{2}(d + p)}{\sin \frac{1}{2}p}$, where p is the internal angle of the prism. In doubly refracting crystals two values of the index of refraction will in general be obtained. The index of refraction of a liquid may be determined by placing it in a hollow prism and proceeding as above.

Other methods of determining the index of refraction depend upon finding the value of the critical angle. For this purpose an instrument known as a **refractometer** is used. Now the critical angle may be determined in two different ways: (1) by total reflection proper and (2) by grazing incidence.

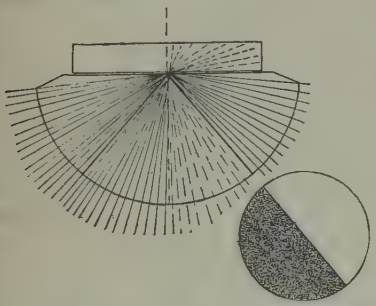


FIG. 308.—Determination of the index of refraction by total reflection.

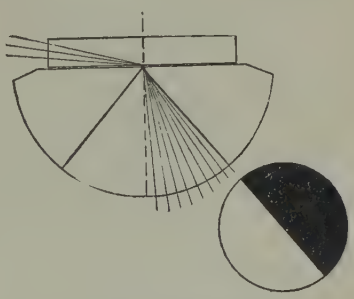


FIG. 309.—Determination of the index of refraction by grazing incidence.

The first method is shown in Fig. 308. The crystal or vessel with enclosed liquid is placed on the upper plane surface of highly refracting glass (a necessary condition is that the glass must have a higher index of refraction than the substance to be tested) and diffused light is directed upward on one side of the glass hemisphere. On striking a substance with higher index of refraction some of the rays will enter the substance but those that meet it at an angle greater than the critical angle will be reflected back into the hemisphere. This will cause half of the field of the telescope to be partially dark and the other half light as

shown in Fig. 308. If the sharp line of demarcation is placed on the cross hairs of the telescope, the critical angle may be read off directly.

In the other method, that of grazing incidence, the light enters the crystal, or liquid in the vessel, from the side, as shown in Fig. 309. In this case the upper side of the telescope field is dark, for no totally reflected light is allowed to fall upon the lower part of the hemisphere.

In the Abbé refractometer the principle of total reflection proper is used, while in the Pulfrich refractometer the method of grazing incidence is employed. Either of these methods may be used for solids or liquids.

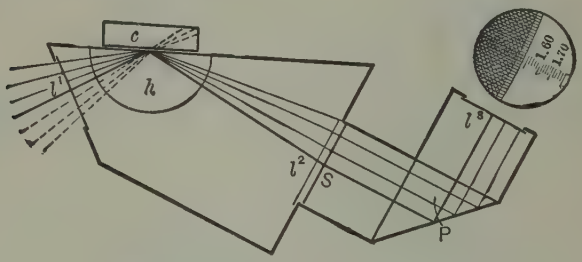


FIG. 310.—The Smith refractometer.

A convenient refractometer for the approximate determination of the refractive indices, especially for cut gem stones, is one devised by G. F. H. Smith of the British Museum. This refractometer is shown diagrammatically in cross-section in Fig. 310. It consists of a metal frame holding a hemisphere, h, of highly refracting glass ($n = 1.79$), a totally-reflecting prism, P, and lenses at l^1, l^2, and l^3. The substance, c, the index of refraction of which is sought, is placed over the glass-hemisphere, h and in close contact with it by means of a drop of α-monobromnaphthalene or methylene iodid. As the glass hemisphere has a greater index of refraction than the substance (this is a necessary condition), rays of light entering at l^1 are in part totally reflected back into

the hemisphere, the rays represented by the dotted lines entering the substance. The totally reflected rays fall on a scale, S, engraved on glass and are reflected by the prism P into the eye-piece at l^3. The field of vision appears as in the circle above the eye-piece; one-half of it is light and the other half dark. After the instrument has been calibrated the index of refraction may be read off directly on the scale. The reading in the figure indicates a doubly refracting substance with indices of refraction of 1.559 and 1.588. Accurate observations should be made in monochromatic light, but examination in white light will indicate the amount of dispersion.

Indirect Determination of the Index of Refraction

A simple, but indirect, method of determining the index of refraction of a mineral is by means of the **Becke test.** Fragments of the mineral are embedded in a liquid of known index of refraction and examined on the stage of a microscope with the diaphragm of the substage partially closed. (In the absence of a diaphragm the substage should be lowered.) On focusing sharply on the edge of the mineral and then throwing it slightly out of focus by raising the microscope tube, a blurred white line will appear on the side of the substance having the greater index of refraction. If the fragment is small enough, the fragment as a whole, not simply the border, will become brighter if its index is greater than that of the liquid and darker if the index is less than that the liquid. On lowering the microscope tube the white line appears on the side of the substance having the smaller index of refraction. The explanation of the Becke test is given in Figs. 311–312. Two fragments are shown embedded in a liquid. The fragment on the left has an index of refraction greater than that of the liquid, while with the one on the right the opposite is the case. The microscope tube is supposed to be raised. In the first case the rays of light on striking the oblique boundary are reflected back into the mineral, for the critical angle is exceeded. In the other case the rays

go on through the mineral because the critical angle is not exceeded. If then the focus is changed to the dotted line shown, it is apparent that there will be a concentration of light toward the fragment in the first case, but not in the second. By using

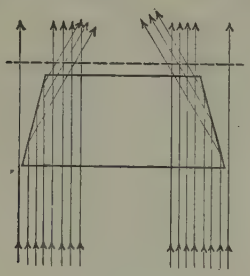


Fig. 311.

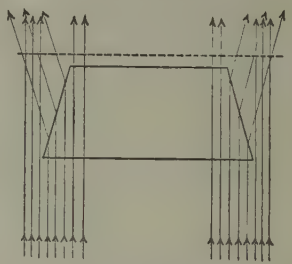


Fig. 312.

Figs. 311–312.—Explanation of the Becke test.

a number of liquids the index may be obtained within certain limits. The most useful liquids are as follows:

Petroleum	1.450±
Turpentine	1.472±
Clove Oil	1.530±
α-monobromnaphthalene	1.658±
Methylene Iodide	1.742±

These liquids may be mixed with each other to form liquids of intermediate indices of refraction. The index of refraction of the liquid must be determined on a refractometer. The Abbé refractometer is especially convenient because only one or two drops of the liquid are necessary and the index may be read off directly. It is convenient to have a series of 30 liquids ranging from 1.45 to 1.74 and differing from each other by 0.01. These liquids should be kept in bottles with double ground glass stoppers so that the index of refraction will remain constant.

Some idea of the index of refraction may also be judged by the appearance of the fragment in the liquid. If the fragment and the liquid have about the same index of refraction, the fragment

will appear smooth and will scarcely be visible; it is said to have **low relief** (Fig. 314). If, on the other hand, the indices of refraction of the two substances are quite different, the surface of the fragment will appear rough and the borders dark. In this case the mineral is said to have **high relief.** It should be noted that the fragment has high relief whether its index is greater (Fig. 315) or less (Fig. 313) than that of the liquid.

In the above explanations it is assumed that the velocity is the same in all directions of the substance. This is true only of amorphous and isometric substances, and even then only under normal conditions. Doubly refracting substances are treated in a later section.

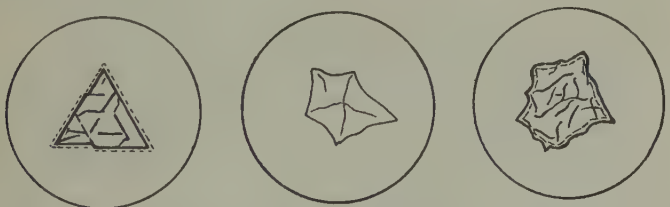


FIG. 313. FIG. 314. FIG. 315.

FIGS. 313–315.—High and low relief of mineral fragments embedded in a liquid.

3. POLARIZED LIGHT

That the light transmitted through a slice of a colored tourmaline crystal cut parallel to the *c*-axis has acquired peculiar properties may be seen by looking at one tourmaline through another similar tourmaline. (The little device known as "tourmaline tongs" shows this very well.) When similar directions of the two tourmalines of the right depth of color are parallel, a maximum amount of light is transmitted, while if similar directions of the tourmalines are perpendicular no light at all is transmitted. The simplest explanation is that the light is vibrating in one plane only. A simple experiment proves that the vibration plane is the one that includes the *c*-axis (the axis of 3-fold symmetry). A beam of light from an arc lamp after traversing the tourmaline

crystal and a colloidal suspension made by adding an alcoholic solution of resin to water has a maximum intensity when the plane of the *c*-axis is normal to the line of sight, but is almost invisible when the plane of the *c*-axis coincides with the line of sight.

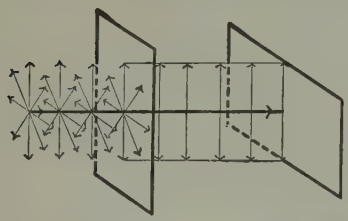


Fig. 316.—Polarization by absorption.

In ordinary light the vibrations are in all planes, while the light transmitted by the tourmaline slice is in but one plane. This light is known as **polarized light.** Figure 316 is a diagrammatic representation of ordinary light and polarized light as transmitted by tourmaline.

The light reflected from non-metallic surfaces such as glass or polished wood is more or less polarized. If the light reflected from a sheet of glass is examined with the tourmaline, it will be found that for a certain angle of incidence (56° for ordinary glass) light is almost extinguished when the *c*-axis of the tourmaline

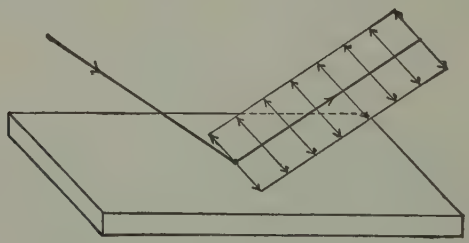


Fig. 317.—Polarization by reflection.

is parallel to the plane of incidence, while a maximum amount of light is transmitted when that direction is perpendicular to the plane of incidence. This means that the reflected light is partially polarized, and that the plane of vibration is perpendicular to the plane of incidence as shown in Fig. 317.

Another method of producing polarized light is by continued

refraction through a series of parallel glass plates. The emerging light is partially polarized and vibrates in the plane of incidence. Figure 318 shows this, as well as the fact that the reflected light is polarized and that the vibrations are in a plane normal to the plane of incidence.

The most practical method of obtaining polarized light is by means of a Nicol prism, but this involves a discussion of double refraction which is the next topic.

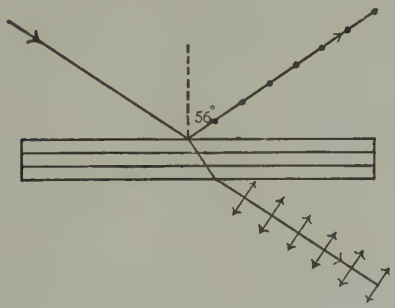


FIG. 318.—Polarization by refraction.

4. DOUBLE REFRACTION

In a dot is viewed through a clear cleavage rhombohedron of calcite (Iceland spar), two images of the dot are seen; on revolution of the calcite one dot remains stationary, while the other dot appears to revolve around the fixed one. A ray of light thus gives rise to two rays, the **ordinary ray** (the fixed one) and the **extraordinary ray** (the one that revolves). In Fig. 319 the image of the ordinary ray is marked *o*, and that of the extraordinary *e*. This phenomenon is known as **double refraction** and though possessed by most minerals, calcite is practically the only transparent mineral in which is it marked enough to be seen with the naked eye.

Light that emerges from a doubly refracting substance such as calcite has acquired peculiar properties, as may be demonstrated

by examining this double image with a tourmaline section cut parallel to the *c*-axis. When the *c*-axis of the tourmaline is parallel to the long diagonal of the calcite rhomb (Fig. 320) only the image due to the ordinary ray, *o*, is seen, but when the

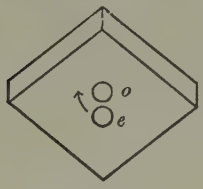


FIG. 319.

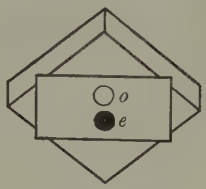


FIG. 320.

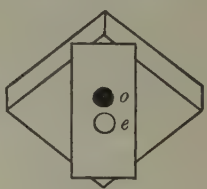


FIG. 321.

FIG. 322*a*.

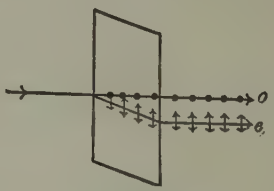


FIG. 322*b*.

FIGS. 319–322*b*.—Double refraction in calcite.

c-axis of the tourmaline is parallel to the short diagonal of the calcite rhomb (Fig. 321) only the image due to the extraordinary ray, *e*, is seen. Hence for the ordinary ray the vibrations are in

FIG. 323.

FIG. 324.

FIG. 325.

FIG. 326.

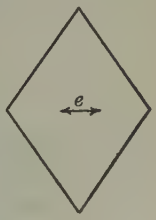
FIG. 327.

FIGS. 323–327.—Experiment with two Iceland spar cleavages.

the plane of the long diagonal and for the extraordinary ray the vibrations are in the plane of the short diagonal. See Figs. 322*a* and 322*b*.

If the double image formed by a piece of Iceland spar be viewed

through another piece of Iceland spar, in general four images are visible, pairs of which wax and wane in turn as one of the Iceland spars is revolved. In certain positions 90° apart, only two images appear. Figures 323–327 show diagrammatically the changes that take place. The symbols *o* and *e* refer to images produced by the first rhomb, while with the second rhomb *o* gives rise to o_o and o_e, and *e* to e_o and e_e.



This behavior is good evidence, if not proof, that **in doubly refracting crystals, light is polarized and is vibrating in two planes which are at right angles to each other.** In Figs. 323–327 the short lines through the circlets indicate the vibration planes.

5. THE NICOL PRISM

The principal device for producing polarized light is a **Nicol prism,** so-called from the name of its inventor, Nicol. It is a piece of apparatus to which we are indebted for much of our knowledge of crystal optics. A clear piece of calcite or Iceland spar (this variety is obtained almost exclusively from cavities in the basalt at a certain locality in Iceland) of suitable dimensions is cut through in a plane at right angles to the principal section and 93° to the terminal faces. After polishing, the two halves are cemented by Canada balsam and mounted. Figure 328 represents a vertical cross-section of a Nicol prism together with a horizontal plan. Now as the refractive index of the ordinary ray of calcite is 1.658 and that of the balsam about 1.54, it will be seen from the figure that the ordinary ray *o*, in passing from the calcite to the balsam cement does not enter the balsam, but is totally reflected and meets the surface at an angle greater than the critical angle

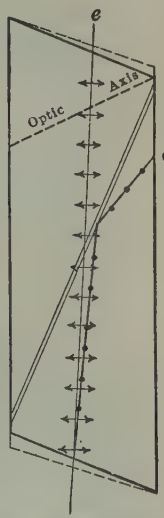


FIG. 328.—Nicol prism.

which is about 68°. The extraordinary ray, *e*, passes on through the balsam cement but slightly affected by the balsam, as for this particular direction of transmission its index of refraction is 1.516. Hence there emerges from the upper surface of the nicol, plane polarized light with vibrations parallel to the short diagonal of the calcite rhomb as indicated in Fig. 328.

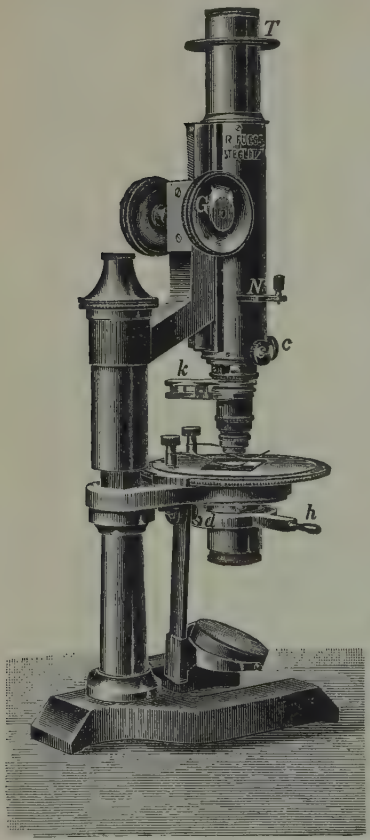


Fig. 329.—Polarizing microscope (¼ size).

If a Nicol prism is examined with a tourmaline, darkness results when the *c*-axis of the tourmaline is parallel to the long diagonal of the calcite rhomb.

If two nicols have their short diagonals parallel, light goes through unaffected, except that the intensity is diminished. If one of the nicols is revolved, the light gradually fades until their short diagonals are at right angles, when darkness results.

6. THE POLARIZING MICROSCOPE

The polarizing microscope, also often called the petrographic microscope (Fig. 329), differs from an ordinary microscope in the addition of a rotating stage for measuring angles and of two Nicol prisms, one above, the other below, the stage. Two nicols are necessary, for the effects due to polarized light cannot usually be distinguished except by another nicol. The lower nicol is called

the **polarizer** and the upper one, the **analyzer.** The lower one fits into a socket so it may be rotated, but ordinarily it is set so that its vibration plane is at right angles to that of the upper nicol. Then the field should be dark and the nicols are said to "crossed."

In some cases we use the lower nicol alone and then its vibration plane should be known. A convenient method of making this determination is to examine crushed fragments of fibrous tourmaline under the microscope. The tourmaline prisms become dark when their long axis is perpendicular to the vibration plane of the lower nicol, as shown in Fig. 330. A thin section of biotite may also be used to determine the vibration plane of the lower nicol. (See p. 202.)

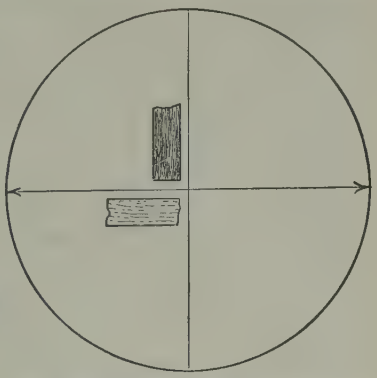


FIG. 330.—Tourmaline fragments in polarized light.

Adjustments of the Polarizing Microscope

The following adjustments of the polarizing microscope must be made in the order indicated.

1. "Crossing" of the nicols.
2. Determination of the plane of vibration of the lower nicol.
3. Placing of the cross-hairs of the eye-piece parallel to the vibration planes of the nicols.
4. Centering the stage (see below).

In order to use the rotating stage, its center must coincide with the optical center of the microscope tube. The method of **centering the stage** may be explained by referring to Fig. 331. A and B are centering screws 90° apart, located either on the stage or on the microscope tube, preferably on the latter. The two perpendicular lines across the field represent the cross-hairs. An object *o* on a glass slide is placed at the intersection of the cross-hairs. Suppose on revolution of the stage it appears to

revolve in the dotted circle until it resumes its original position. Then revolve the stage 180°, correct for one-half the error by the centering screws, the other half by moving the slide on the stage. In the figure the error is oo', the components of which in the direction of the cross-hairs are $o'e$ and $o'd$. They by the centering screw A, o' is first moved the distance $\frac{1}{2}o'e$ and by the centering screw B, o' is moved the distance $\frac{1}{2}o'd$. The object, o, then takes the position c and the slide itself must be moved the distance co, when the stage should be approximately centered. It may be necessary to repeat the operation several times for accurate centering.

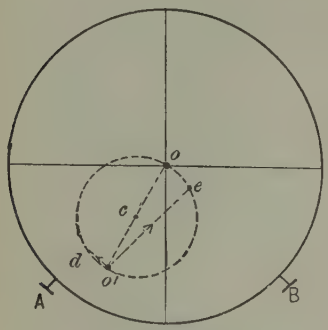


FIG. 331.
Method of centering the stage.

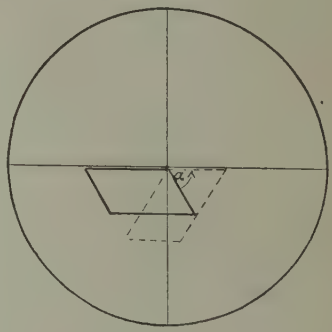


FIG. 332.
Method of measuring an angle.

To measure a plane angle in a thin section or the interfacial angle of a small, flat crystal the stage is centered with the intersection of the two edges at the center of the cross-hairs. A reading is made when one edge of the crystal is parallel to the east-west cross-hair, say, then the stage is revolved until the other edge (dotted line in Fig. 332) is parallel to the same cross-hair, but on the opposite side of the center, when another reading is taken. The difference between the two readings is the supplement or external angle (α in the figure).

The microscope is often used for measuring very small distances

such as the dimensions of minute crystals. For this purpose a special eye-piece (micrometer eye-piece) containing a scale etched on glass is used. On the stage of the microscope a scale reading hundredths of a millimeter is placed. It is then necessary to see how many hundredths of a millimeter each division of the eye-piece is equivalent to.

7. INTERFERENCE COLORS

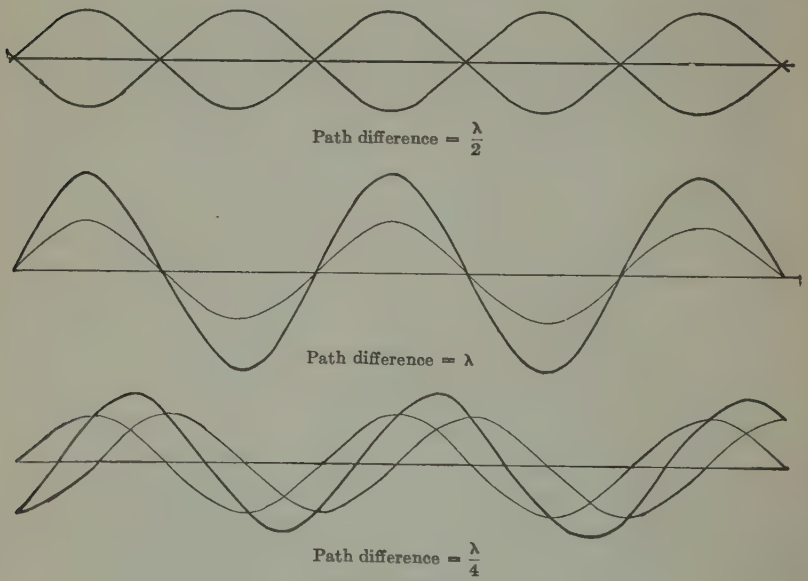
If thin plates of singly refracting (isometric) crystals are examined between crossed nicols there is no result, for the original field remains dark. But if thin plates of doubly refracting crystals are examined between crossed nicols there result the beautiful color effects known as **interference colors.** In order to explain these colors it is necessary to consider the results obtained in examining the doubly refracting plates in monochromatic light. If two light waves or train of waves of the same wave-length travel along the same path, after they have traveled different distances in another medium, they combine in general to produce a new wave, the ordinate at any point of which is equal to the sum of the ordinates of the two original waves. This phenomenon is called **interference.**[1]

There are two special cases of importance. (1) The two waves have the same amplitude and a path difference of $\frac{1}{2}\lambda$. As can be seen from Fig. 333 they neutralize each other and darkness is the result. That is, under certain conditions two light waves can combine so as to produce darkness. (2) The two waves have the same amplitude and a path difference of λ. In this case the new wave will have the same wave length, but the amplitude will be doubled (Fig. 334). For intermediate cases such as path difference of $\frac{1}{4}\lambda$, the resultant wave will have an intermediate amplitude (Fig. 335). Interference results when light waves from the same source go over the same path, one in advance of the other. There are two methods of obtaining interference, one by

[1] The interference in this case is destructive; constructive interference is produced by diffraction.

the use of thin films, the other by the use of doubly-refracting crystals.

Let Fig. 336 represent a thin film of air in a selenite cleavage. AB and A′B′ are oblique incident rays. On reaching the surface of the film they are partly reflected and partly refracted. So that for a point B′ there will be two rays traveling along B′D′; one of them is the reflected ray of A′B′, the other the reflected ray



FIGS. 333–335.

of the refracted ray EC. These two rays are in a position to interfere for one of them has traveled a greater distance than the other. For while one has traveled A′B′ the other has traveled ABE. Hence the ray from AB is the distance ECB′ behind the ray from A′B′.

If we use monochromatic light and adjust the thickness of the film so that the retardation, or lagging of one ray behind the

other, is equal to $\frac{1}{2}\lambda$, we have, for that particular thickness, darkness, while for a retardation of λ we have light of maximum intensity. Therefore with a wedge-shaped film in monochromatic light we have a series of dark bands, for retardations of $n/2\ \lambda$ and $n\lambda$ produce the same effect as $\frac{1}{2}\lambda$ and λ respectively.

Now let us consider the case of doubly-refracting crystals. A series of parallel light waves from the polarizer or lower nicol enter the crystal and are broken up into two sets of waves, one vibrating in the plane of the paper, say, and the other in the plane normal to the paper. See Fig. 337. At certain points on the upper surface there will emerge two sets of waves traveling

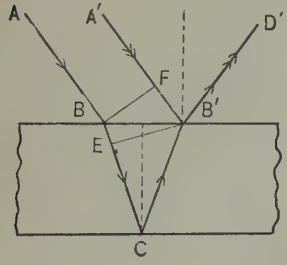


Fig. 336.

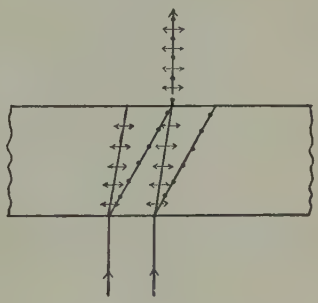


Fig. 337.

in the same path but vibrating in planes at right angles to each other, and oblique to the planes of vibration of the nicols. In order that they may interfere it is necessary to reduce the vibrations to one plane and for this purpose an analyzer or upper nicol is necessary. The effects produced depend upon the relative positions of the nicols, upon the position of the crystal with reference to the nicols, and upon the path difference of the two sets of polarized light waves.

Figure 338 explains diagrammatically what happens when a doubly refracting crystal is examined between the crossed nicols of a polarizing microscope. A ray of light entering the lower

nicol is broken into two rays, e and o. One of these (o) is totally reflected and disappears. The remaining ray (e) is broken into two rays (e' and o') by the mineral plate. These two rays, which

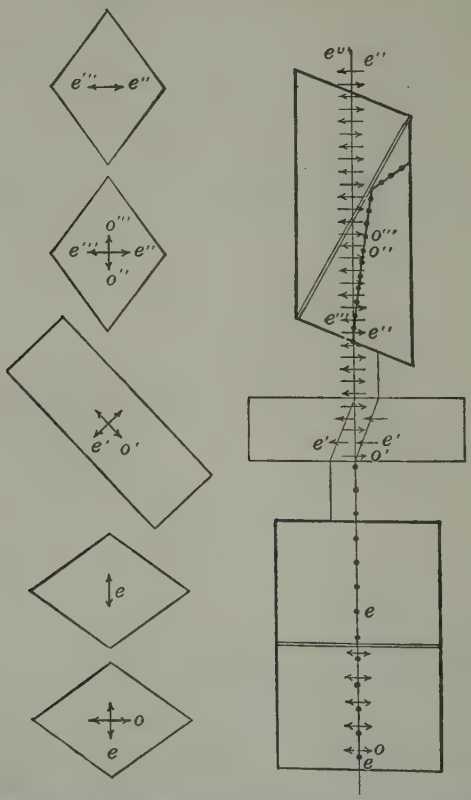


FIG. 338.—Diagrammatic representation of doubly refracting crystal examined between crossed nicols.

are vibrating at right angles to each other, are each broken into two rays (e'', o'', and e''', o'''), by the upper nicol. One from each of these (o'' and o''') is totally reflected and finally there emerge from the top of the upper nicol two sets of waves (e'' and

e''') vibrating in the same plane and these interfere with each other.

With crossed nicols darkness results when the path difference is λ. In Fig. 339, PP′ is the vibration plane of the lower nicol and AA′ of the upper nicol, RR′ and SS′, the vibration planes of the crystal plates. The distances *or* and *os* represent vibrations in the same phase. The components of these in the plane of the upper nicol are $o\rho$ and $o\sigma$, which are opposite and equal. Hence

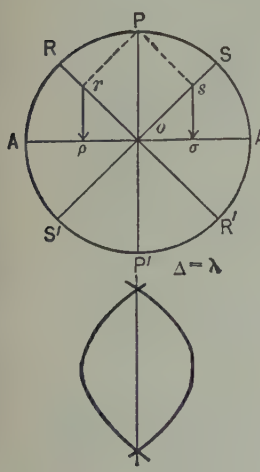


Fig. 339.

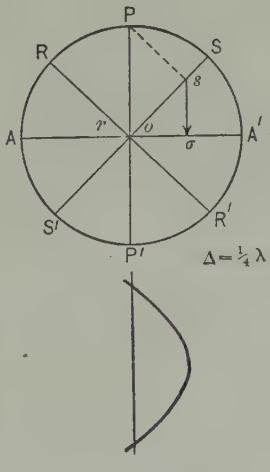


Fig. 340.

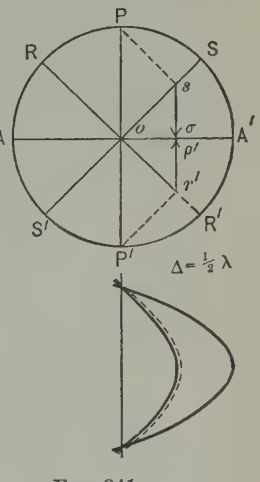


Fig. 341.

they annul each other. With crossed nicols there is maximum light when the path difference is $\frac{1}{2}\lambda$. In Fig. 341, r' and s represent vibrations of $\frac{1}{2}\lambda$ path difference. Their components in the plane of the upper nicol are ρ' and σ, equal but on the same side of the origin. Hence the intensity is doubled. For a path difference of $\frac{1}{4}\lambda$, we have the intensity shown in Fig. 340. Thus the intensity varies between 0 for a retardation of λ, and a maximum for retardation of $\frac{1}{2}\lambda$.

As can be seen from Fig. 342, the retardation produced by a

wedge-shaped section of a crystal will vary from point to point. A retardation of $n\lambda$ will give darkness and a retardation of $n/2\ \lambda$ will give a maximum intensity. Hence a wedge examined in monochromatic light beween crossed nicols will appear as a series of parallel dark bands interspersed with colored spaces.

For white light we have the combined effect of all the colors of the spectrum. Some idea of the interference colors seen in white light may be gained by a study of Fig. 343. (This diagram may be colored by the student.) The top of the figure represents a wedge-shaped section as viewed in various kinds of monochromatic light, there being a dark band at positions which give retardations of $n\lambda$. For each of these colors a medium value of

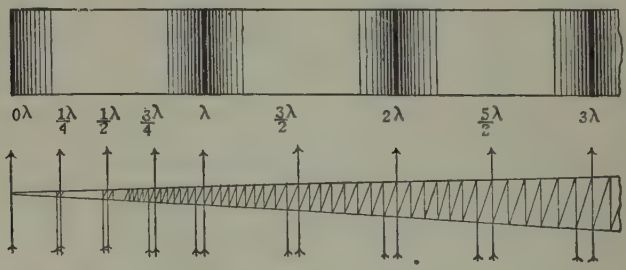


Fig. 342.—Wedge of a doubly-refracting crystal between crossed nicols.

the wave length is chosen as follows: red, 700$\mu\mu$; orange, 620$\mu\mu$; yellow, 560$\mu\mu$; green, 515$\mu\mu$; blue, 460$\mu\mu$; violet, 410$\mu\mu$. The top row of figures gives the value of retardations in $\mu\mu$.

The lower part of the figure indicates the interference colors as seen in white light. Let us consider the colors in succession. The intensity of different parts of the spectrum varies and has an influence in determining the color. Yellow-green is the most intense, and violet, the least intense part of the spectrum. The **interference color chart,** as it is called, begins with darkness, succeeded by dark gray which gradually becomes lighter. At about 250$\mu\mu$ all the colors combine to form white light. At 280$\mu\mu$($\frac{1}{2}\lambda$ for yellow) yellow is at a maximum, but mixed with

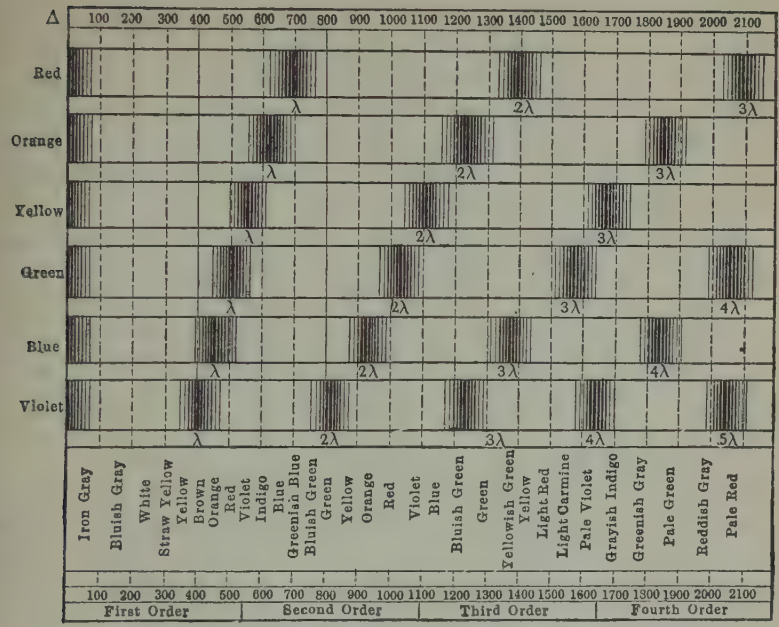


FIG. 343.—The derivation of the interference color chart.

white it gives straw yellow. At 310$\mu\mu$ and at 350$\mu\mu$, orange and red respectively, are at a maximum, but the great intensity of the yellow modifies these colors and places them further to the right, for at 360$\mu\mu$ the color is bright yellow. At about 550$\mu\mu$, violet is the color. Though of weak intensity, violet is produced here because the other colors are practically extinguished. As can be seen from the diagram the colors follow in order: blue, green, yellow, and red. At about 1100$\mu\mu$, violet appears again. At this point only red, blue, and violet are near a maximum. But red and blue together produce violet. Then in order we have blue, green, yellow, and red again. These same colors are repeated a second time but become paler and then pass into neutral tints (largely pink and pale green) and finally into high-order white which resembles ordinary white light.

There is a repetition in the colors, but they gradually become fainter. The colors from black up to the first violet ($\Delta = 550\mu\mu$) are called **first-order** colors, from this violet up to the second violet ($\Delta = 1100\mu\mu$), **second-order** colors, and so on. In white light seven or eight orders may be distinguished, but in monochromatic light there is no limit to the number of orders as determined by the dark bands.

By trial it may be found that the interference color depends upon three factors: (1) the double refraction which is a constant for the crystal, (2) the orientation or direction in which the crystal is cut (*e.g.*, in a thin section of sandstone the quartz grains, cut in various directions, have a great variety of interference colors), (3) the thickness, as may be seen in a quartz or gypsum wedge.

The formula $\Delta = t(n_1 - n_2)$ gives the relation between Δ, the retardation in $\mu\mu$, t, the thickness of the plate, and $(n_1 - n_2)$, the double refraction; n_1 and n_2 are the two values of the indices of refraction for a particular section. For a given substance with known indices of refraction the thickness may be measured and the interference colors predicted. Or the thickness may be measured, the retardation determined from the color chart, and the double refraction calculated. Or the thickness may be calculated that will give a certain interference color for a crystal with known double refraction. In the interference color chart of Fig. 344, the horizontal lines represent the thickness from 0.00 to 0.06 mm.; ordinary rock slides and fragments are from 0.03 to 0.05 mm. in thickness. The vertical lines give retardations in $\mu\mu$, while the diagonal lines represent the amount of the double refraction. A crystal of 0.03 mm. thickness and double refraction of 0.02 has a retardation of $600\mu\mu$ ($0.000600 = 0.03 \times 0.02$), and gives a second-order indigo blue interference color. Fig. 344 may be colored to correspond to the colors given at the bottom of Fig. 343; the names of the common minerals may be written in the blank space to the left in the appropriate position according to the double refraction.

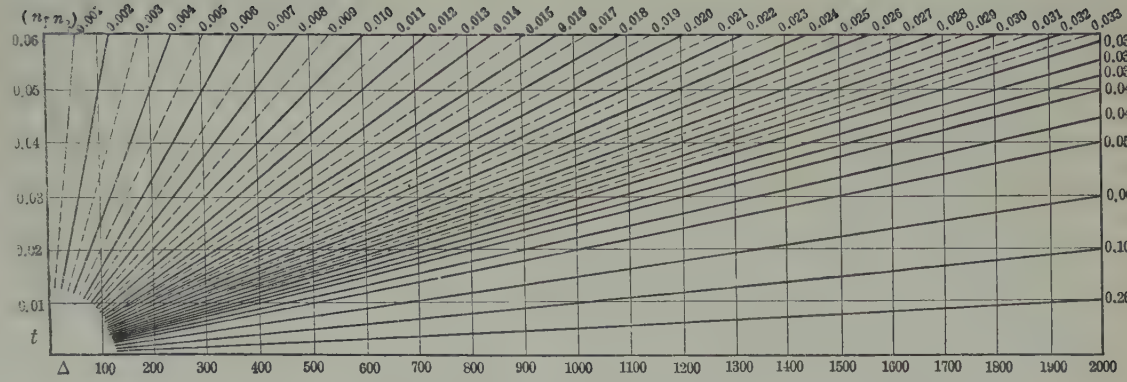


FIG. 344.—The interference color chart.

8. VIBRATION OR EXTINCTION DIRECTIONS

If a section of a doubly refracting crystal is revolved between crossed nicols there is darkness four times in a complete revolution. This is called **extinction** and is simply due to the fact that for these particular positions the crystal has no effect upon the dark field produced by the crossed nicols. The two directions in the crystal parallel to the vibration planes of the two nicols are called **extinction directions** or vibration directions. These two directions are directions of the two plane polarized waves produced in doubly refracting crystals by the plane-polarized light of the lower nicol.

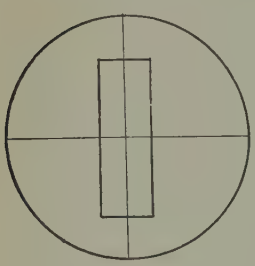


FIG. 345.
Parallel extinction.

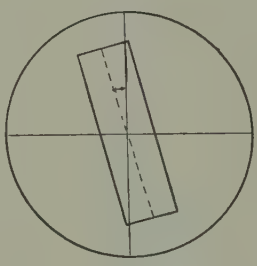


FIG. 346.
Oblique extinction.

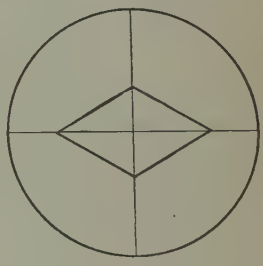


FIG. 347.
Symmetrical extinction.

Now according to the position of these directions with reference to the crystal outlines we have various kinds of extinction characteristic of crystals of the various systems. In case the directions are parallel to the outline we have **parallel extinction.** This is represented by the convention of Fig. 345, the cross-hairs of the microscope being parallel to the vibration-planes of the nicols, and the crystal placed in the position of darkness. If the directions are not parallel to the outline we have **oblique extinction** (Fig. 346). The particular case in which these directions make equal angles with the edges of the crystal is called **symmetrical extinction** (Fig. 347).

The angle between an extinction direction and a prominent crystallographic direction of a crystal (usually the *c*-axis) is called the **extinction angle,** and is characteristic of certain crystals in certain directions. The extinction angle is determined by taking a reading when the outline is parallel to one of the cross-hairs (the stage being centered) and then revolving the stage until maximum darkness results, when another reading is taken. The difference between the two readings is the extinction angle. In Fig. 346, the extinction angle indicated by the arrow is 15°. It may be noticed that there are two possible extinction angles which are complementary. The smaller angle ($<45°$) is usually taken.

Accurate determinations of the extinction angle are made in monochromatic light. A convenient determination in white light may be made by using a gypsum plate which gives a field showing red of the first order. This is called the **sensitive tint,** for the least change gives either orange-red or violet-blue. When inserted in the slot provided for test-plates, a doubly refracting crystal appears the same tint of red as the red field only when it is in the extinction position.

9. THE DETERMINATION OF THE INDICES OF REFRACTION IN DOUBLY-REFRACTING CRYSTALS

For a section of a doubly-refracting crystal cut in any direction there are in general two values of the index of refraction, one for each of the two vibration directions at right angles to each other. These two directions are the extinction positions for the particular section. After bringing the crystal plate or fragment into extinction, one index of refraction is determined with reference to the set of liquids described on p. 166. Then after revolving the stage of the microscope 90°, the other index is determined in exactly the same way. See Fig. 348.

The two values of the index of refraction may be designated n_1 and n_2, and their difference $(n_1 - n_2)$ is the double refraction or birefringence for the particular section. The vibration direc-

tion of the two rays of the doubly-refracting substance are at right angles to each other.

For a given doubly-refracting crystal cut in various direction a good many different values of n_1 and n_2 may be obtained. The maximum of all possible values of n_1 is denoted by n_γ, and the minimum of all possible values of n_2 is denoted by n_α. Some particular section, which may be recognized by the fact that it has the highest interference color for a given thickness, will furnish both n_γ and n_α. In addition to n_γ and n_α, a great many intermediate values may be obtained. In orthorhombic, monoclinic, and triclinic crystals (these are collectively called biaxial) a section cut normal to the plane of α and γ furnishes an important intermediate (not a mean) value known as n_β. The fact that the value n_β always lies between (except in the rare cases in which it is exactly equal to one or both of them) the two values of n_1 and n_2 found on any section enables one to determine it by trying fragments in various liquids until a liquid is found, the index of refraction (n_3) of which is greater than that for various fragments ($n_3 > n_1 > n_2$) and also another liquid, the index of refraction (n_4) of which is less than that of various fragments ($n_4 < n_2 < n_1$). Then n_β lies between n_3 and n_4.

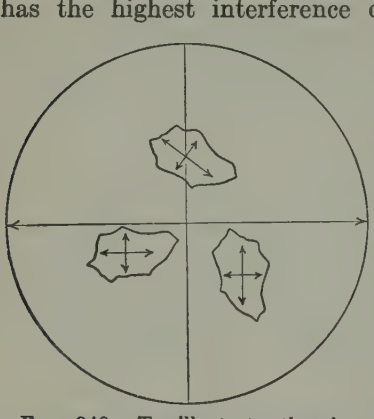


FIG. 348.—To illustrate the determination of indices of refraction in doubly-refracting crystals.

The above discussion implies that the mineral fragments have no cleavage, and hence all possible orientations are obtained. If, however, a mineral has good cleavage, it may not be possible to determine the three principal indices of refraction n_α, n_β, and n_γ. In colemanite, for example, the two values n_β and n_γ are obtained, but not n_α, on account of the good cleavage parallel to (010).

10. DIRECTION OF THE FASTER AND SLOWER RAY

For a section of a doubly-refracting crystal cut in any direction there are in general two values of the index of refraction corresponding to the two vibration directions at right angles to each other. One of the values is greater than the other, otherwise there would be no double refraction. Interference in doubly-refracting crystals is caused by one ray getting behind the other. The one that is retarded is called the slower ray, the other, the faster ray. The ray with the greater index of refraction is the **slower ray,** and the one with the smaller index of refraction is the **faster ray.**

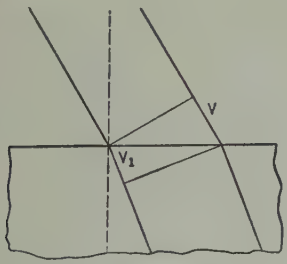


FIG. 349.—Faster ray.

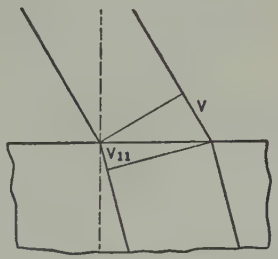


FIG. 350.—Slower ray.

FIGS. 349–350.—To show the reciprocal relation of velocity and index of refraction.

This reciprocal relation of velocity and index of refraction may be proved by means of Figs. 349 and 350. The two figures are sections taken at right angles to each other. Figure 349 represents the **faster ray** and Fig. 350 the **slower ray.** In Fig. 349 the index of refraction is about 1.33 and the velocity is V_1 in terms of V, the velocity in air, while in Fig. 350 the index of refraction is about 1.92 and the velocity is V_{11} in terms of V.

The determination of the faster and slower ray may be made by determining the indices of refraction as outlined in the preceding section, but this is not always convenient. Another method is based upon the fact that the superposition of one

doubly-refracting section on another has the same effect as thickening or thinning the section by causing the interference colors to go up or down on the interference color chart; "up" is toward the thick end of a wedge and "down" toward the thin end of a wedge. Several **test-plates** are used for this purpose. The one most frequently used is the **mica plate,** a cleavage of muscovite of a thickness sufficient to produce a retardation of 140$\mu\mu$ ($\frac{1}{4}\lambda$ for medium yellow, and hence called the quarter-undulation mica plate).[1] The direction of the slower ray of this plate is marked by an arrow. (This direction is the line joining the

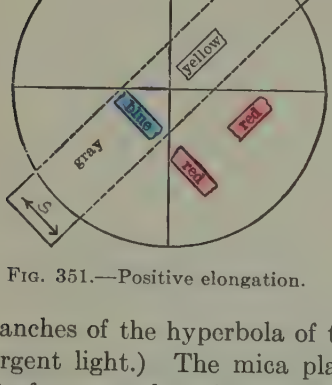


FIG. 351.—Positive elongation.

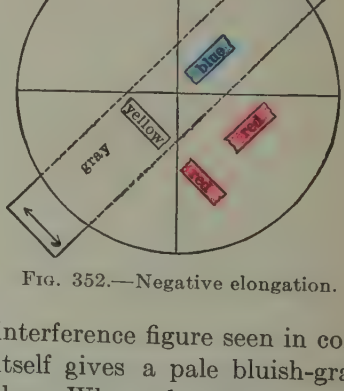


FIG. 352.—Negative elongation.

branches of the hyperbola of the interference figure seen in convergent light.) The mica plate itself gives a pale bluish-gray interference color of the first order. When placed in the slot provided for the purpose in the lower end of the microscope tube it causes the interference color of a crystal section placed in the position of maximum illumination to be lowered or raised by 140$\mu\mu$ (see color chart p. 181). The color goes "up" when similar directions are parallel (when slower ray of crystal coincides with slower ray of the mica plate) and "down" when dissimilar directions are parallel (when slower ray of crystal coincides with faster ray of the mica plate or vice versa).

[1] The correct thickness of this plate may be judged by the fact that the first ring of the interference figure is a complete ellipse.

This test is often employed to determine the elongation of the crystal, that is, to find whether the long direction of the crystal is the slower ray or the faster ray. Examples of the two cases are given in Figs. 351 and 352, the dotted rectangle representing the mica plate with arrow indicating the slower ray. In the first case, the crystal originally with red interference color is changed to blue, when its length is parallel to the arrow of the mica plate. Hence the elongation is parallel to the slower ray. This is called **positive elongation.** In the other case, the red crystal is changed to blue, when its length is parallel to the faster ray of the mica plate, (the faster ray is always perpendicular to the slower ray). This is called **negative elongation.**

11. CLASSIFICATION OF CRYSTALS FROM AN OPTICAL STANDPOINT

From an optical standpoint there are three divisions of crystals: isotropic (isometric), uniaxial (tetragonal and hexagonal), and biaxial (orthorhombic, monoclinic, and triclinic). In discussing the optical properties it is convenient to employ a geometrical representation of the optical structure. The figure formed by taking as radius vector the index of refraction in various directions is called the **optic ellipsoid.**[1] The optic ellipsoid is, in general a triaxial ellipsoid, sections of which are ellipses. The important property of the ellipsoid is that the major and minor axes of any elliptic section or **optic ellipse** are the extinction directions for that section and, moreover, the lengths of these axes are proportional to the indices of refraction for that particular section. The shape of the ellipsoid varies for the three divisions of crystals mentioned.

In isometric crystals the index of refraction is the same for all directions. The optic ellipsoid is therefore a sphere. All sections of a sphere are circular, so there is no double refraction

[1] There are a number of other ellipsoids used in crystal optics but since the index of refraction is the most fundamental optical constant, the above designated one may be called the optic ellipsoid.

and, hence, no interference colors. A section cut in any direction will remain dark between crossed nicols. Isometric crystals and amorphous substances such as glass are said to be **isotropic.** Crystals of the remaining systems (those except the isometric) have double refraction; for these the term **anisotropic** is used in contrast with the term isotropic.

Tetragonal and hexagonal crystals constitute the **uniaxial** division. If sections of these crystals, cut in various directions, are examined between crossed nicols, it is found that basal sections (sections perpendicular to the *c*-axis) remain dark between crossed nicols, and that all sections parallel to the *c*-axis give some interference color which is a maximum for a given thickness, while sections oblique to the *c*-axis give interference colors varying from a maximum to darkness (the color depends upon the obliquity), but those of equal obliquity to the *c*-axis give the same interference color.

From these tests it will be seen that the optic ellipsoid is an ellipsoid of revolution. The axes of an elliptical section through the *c*-axis represent the indices of refraction, one of which (designated n_γ), is the maximum of all possible values in the crystal, while the other (designated n_α), is the minimum of all possible values. In some cases γ,[1] or the slowest ray, is parallel to the *c*-axis, while in other cases, α, or the fastest ray, is parallel to the *c*-axis. This divides the uniaxial crystals into two divisions, the **optically positive** ($c = \gamma$) and the **optically negative** ($c = \alpha$); here the terms positive and negative are purely arbitrary. The ellipsoid of positive crystals is in reality an oblate spheroid and that of negative crystals, a prolate spheroid, because the extreme values of the indices of refraction are not very different except in a few cases such as that of calcite.

The determination of the **optical character,** that is, whether positive or negative, is made by ascertaining the faster and slower ray in a section parallel to the *c*-axis, or in a basal section by

[1] α and γ are directions in a crystal, and n_α and n_γ are indices of refraction for these directions.

testing the interference figure, obtained by convergent light, with a mica plate.

Crystals of the remaining systems, orthorhombic, monoclinic, and triclinic, constitute the **biaxial** division. Of all the possible values of the indices of refraction in a biaxial crystal it is found that one section contains the direction γ corresponding to the maximum index of refraction n_γ, and also the direction α corresponding to the minimum index of refraction n_α. For other sections the indices of refraction are intermediate between the maximum and minimum. The direction perpendicular to the plane of γ and α is called β, or sometimes the **optic normal.** The index of refraction n_β is intermediate between n_γ and n_α, but is *not* a mean value and is recorded simply because it is one of the values for sections cut normal to α and to γ.

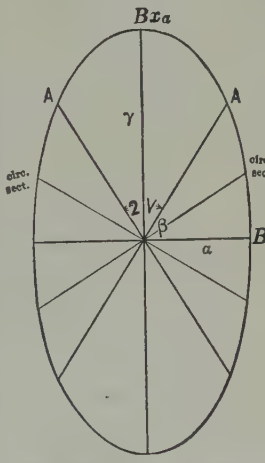


FIG. 353.—Section of the optic ellipsoid of a biaxial crystal containing α, γ, and the optic axes.

The optic ellipsoid for biaxial crystals made by laying off on three rectangular axes the values n_α, n_β, and n_γ (indices of refraction for the three directions mentioned) is a triaxial ellipsoid. The maximum interference color for a given thickness is given by the section which includes γ and α. The interference colors vary from this maximum to a minimum, but there is no section that remains dark between crossed nicols as in uniaxial crystals.

Figure 353 is the section of a triaxial ellipsoid which contains γ and α. There are two circular sections of this ellipsoid. Lines normal to these circular sections are peculiar directions corresponding somewhat to the single direction or *c*-axis of uniaxial crystals. These directions are called **optic axes,** hence the term biaxial. A plate of a biaxial crystal normal to an optic

axis appears uniformly bright between crossed nicols for all positions of rotation. The optic axes always lie in the plane of γ and α, which is therefore called the **plane of the optic axes** or the axial plane; the acute angle between the optic axes is called the **axial angle** (denoted by the term $2V$). In Fig. 353, OA and OA′ are the optic axes and AOA′ the axial angle. The optic axes are always symmetrically placed with respect to γ and α.

SYNOPSIS OF THE OPTICAL PROPERTIES AND CONSTANTS FOR THE CRYSTAL SYSTEMS

ISOTROPIC	Optic ellipsoid a sphere	ISOMETRIC	All sections remain dark	n	No interference figure		
ANISOTROPIC	UNIAXIAL Optic ellipsoid a spheroid of revolution	TETRAGONAL	Basal section dark. Parallel extinction in most other sections	n_α, n_γ	Interference figure with dark cross and colored circles		
		HEXAGONAL					
	BIAXIAL Optic ellipsoid a triaxial ellipsoid	ORTHORHOMBIC	Parallel extinction in most sections.	n_α, n_β, n_γ	Interference figure with dark hyperbola and colored ellipses and lemniscates.	Symmetrical dispersion.	2V
		MONOCLINIC	Parallel extinction in 100, 001, and $h0l$ sections. Oblique in others.			Horizontal, inclined, or crossed dispersion.	
		TRICLINIC	Oblique extinction in all sections			Asymmetric dispersion.	

The line bisecting the axial angle is called the **acute bisectrix** (denoted by Bx_a). The line bisecting the obtuse angle between the optic axes is called the **obtuse bisectrix** (denoted by Bx_o).

There are two divisions of biaxial crystals according to whether the acute bisectrix is γ or α. The former are called **positive** ($Bx_a = \gamma$), and the latter, **negative** ($Bx_a = \alpha$); this is a purely arbitrary designation. Figure 353 represents a positive crystal.

The determination of the optical character may be made by testing for the faster and slower ray in a section known to be perpendicular to the acute bisectrix. It may also be determined in this kind of section by obtaining an interference figure and testing it with a mica plate.

The optical properties for the crystal systems may be tabulated as in the preceding table.

12. INTERFERENCE FIGURES

The tests mentioned up to this point have been made by using ordinary **parallel light** or polarized parallel light. A unique series of effects, important in the identification and description of minerals, may be obtained by examining suitable sections in **convergent polarized light.** For this purpose either a polariscope or a polarizing microscope may be used. A **polariscope** is an instrument consisting essentially of an analyzer and a polarizer with slight magnifying power and strongly convergent lenses both above and below the stage.

If the polarizing microscope is used, a high power objective (Focal length = 3 to 5 mm.) and also a condensing lens placed just below the stage must be substituted for the ordinary set-up. Either the eye-piece must be removed, or a special lens, called the Bertrand lens, must be inserted in the microscope tube between the analyzer and the eye-piece.

The color effects seen when basal sections of uniaxial crystals and sections of biaxial crystals cut normal to the acute bisectrix, are examined in convergent light between crossed nicols are known as **interference figures.**

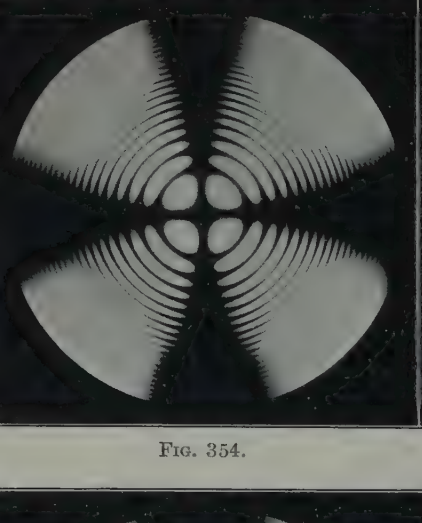


Fig. 354.

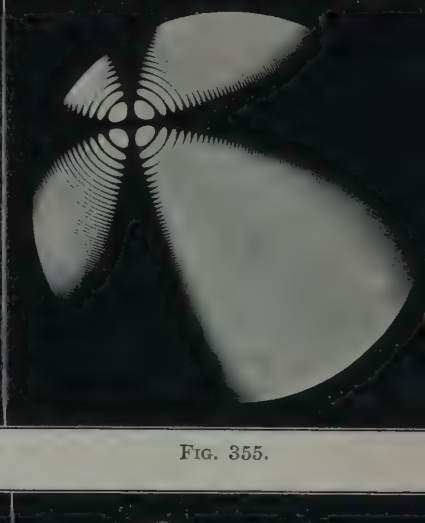


Fig. 355.

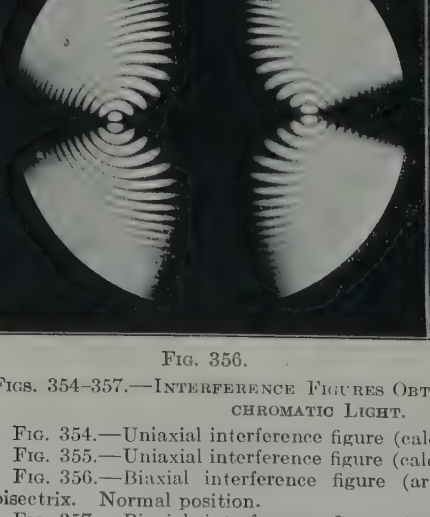


Fig. 356.

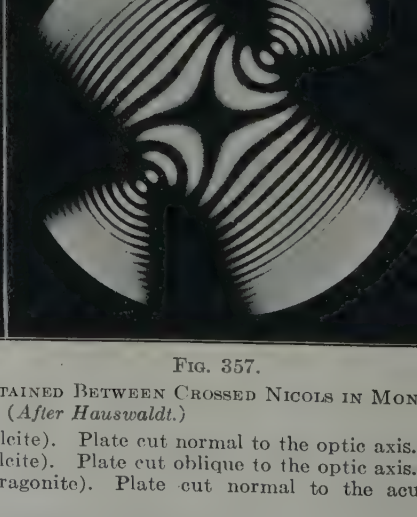


Fig. 357.

Figs. 354–357.—Interference Figures Obtained Between Crossed Nicols in Monochromatic Light. (*After Hauswaldt.*)

Fig. 354.—Uniaxial interference figure (calcite). Plate cut normal to the optic axis.

Fig. 355.—Uniaxial interference figure (calcite). Plate cut oblique to the optic axis.

Fig. 356.—Biaxial interference figure (aragonite). Plate cut normal to the acu bisectrix. Normal position.

Fig. 357.—Biaxial interference figure (aragonite). Plate cut normal to the acu bisectrix. Diagonal position.

With isometric crystals no interference figures are obtained, for there is no double refraction. Double refraction is necessary for the production of interference figures. In fact, interference figures are simply the result of interference colors, due to varying double refraction in different directions, combined and modified by the darkness due to crossed nicols.

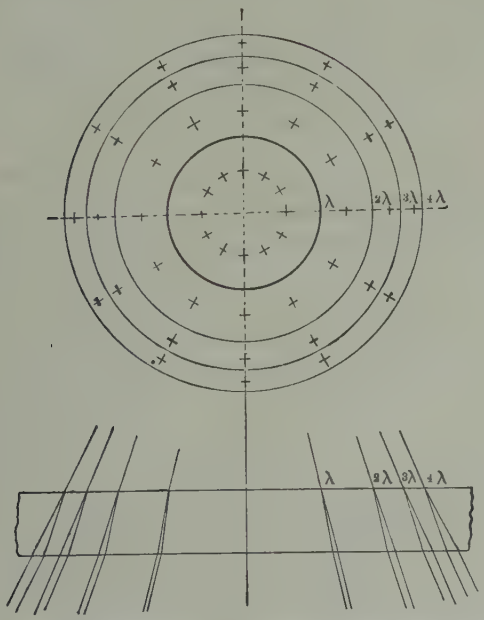


FIG. 358.—Explanation of a uniaxial interference figure.

Basal sections of uniaxial crystals examined in monochromatic convergent light between crossed nicols give a dark cross with dark concentric rings (Fig. 354). The explanation is as follows: (see Fig. 358). Strongly convergent rays of light traverse the crystal in various oblique directions and the effect is the same as if rays of parallel light were transmitted through a wedge of the crystal. Therefore, along any radius we get a dark band

where the retardation is $n\lambda$ for the particular light used. Midway between the bands we get the maximum color. As the structure is the same all around the *c*-axis in uniaxial crystals, the dark bands are circular. It remains to explain the dark cross, which, it should be noticed, is stationary on rotation of the section on the stage. The crystal, it may be imagined, is made up of innumerable parts, each with extinction directions at right angles. These parts are arranged radially around a center, and on rotation of the stage, as vibration directions of successive parts become parallel to the vibration directions of the nicols, darkness results for that particular part. As new radii are always coming into the extinction position there is always a dark cross, the arms of which are parallel to the vibration directions of the two nicols and so remain fixed. That the optic axis is simply a direction in the crystal may be proved by the fact that the interference figure remains the same when the crystal plate is moved about on the microscope stage.

For sections not quite parallel to the basal plane, the dark cross on rotation of the stage is eccentric, but the arms always remain parallel to the vibration planes of the nicols and revolve in the same direction in which the stage is rotated (see Fig. 355).

With ordinary white light we still have the black cross, but the dark rings become colored rings,[1] the colors of which vary from black at the center, through gray, white, yellow, red, blue, green and so on, until after six or seven orders there is practically white light. The number of rings depends upon the thickness and also upon the double refraction. In very thin sectons there may be no rings visible. Very thick sections show the full number of rings. Quartz with weak double refraction shows for ordinary thickness no rings at all, while calcite with very strong double refraction shows a large number of rings.

The optical character of a uniaxial crystal may be determined from the interference figure by inserting in the slot of the micro-

[1] The rings may appear to be dark on account of the weak intensity of the violet portions but the borders at least are colored.

scope tube just above the objective, a mica plate with the slower ray, γ, in the 45° position. The interference figure is changed, the dark cross disappears and two dots appear in two opposite quadrants, as represented diagrammatically in Fig. 359. If the imaginary line joining the two dots is perpendicular to γ of the mica plate, the crystal is positive (as in Fig. 359*a*), while if parallel to γ of the mica plate, it is negative (as in Fig. 359*b*). This is due to the fact that the interference colors "go up" in two opposite quadrants and "go down" in the other two quadrants. The rings, then, are not continuous, but broken, and the two rings nearest the center form the two dots.

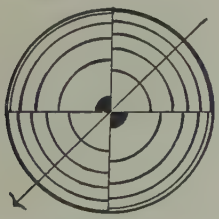


FIG. 359*a*.

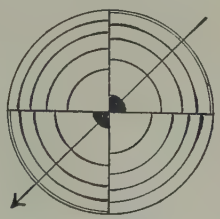


FIG. 359*b*.

FIGS. 359*a*–359*b*.—Uniaxial interference figures with superimposed mica plate.

Sections of biaxial crystals cut normal to the acute bisectrix show an interference figure like that of Fig. 356, with a black cross and two sets of concentric ellipses passing into 8-shaped curves (lemniscates). In monochromatic light the rings are dark and in white light, colored. On revolving the section on the stage, the dark cross opens up and passes into hyperbolæ as shown in Fig. 357, which represents the 45° position. The line joining the centers of the ellipses is the trace of the axial plane; the centers of the ellipses represent the emergence of the optic axes.

The biaxial interference figure may be explained by means of the diagrammatic Fig. 360. For monochromatic light the optical structure of biaxial crystals is symmetrical to three planes at

right angles to each other. One of these is the plane of the paper, while the other two are represented by their traces, the vertical and horizontal lines of the figure, which are also vibration planes of the two nicols. The two circlets are traces of the optic axes. The extinction directions for various parts of a crystal may be obtained by bisecting, internally and externally, the angles formed by joining any point with the traces of the optic axes. The dotted lines represent this procedure for one point. In similar manner the small crosses were obtained for different

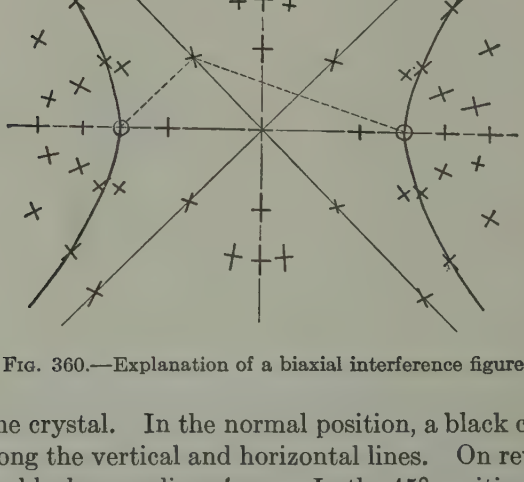


FIG. 360.—Explanation of a biaxial interference figure.

parts of the crystal. In the normal position, a black cross will be formed along the vertical and horizontal lines. On revolving the section the black cross disappears. In the 45° position brush-like hyperbolæ are formed by the darkness of different parts along the hyperbolæ of the figure. In the 90° position the cross is restored.

The number of rings depends upon the strength of the double refraction and upon the thickness, but the distance between the vertices of the hyperbolæ remains constant whatever the thickness.

The optical character is determined by means of a quartz

wedge on which is marked the slower ray γ. The quartz wedge is inserted in the slot, thin end first, when the interference figure shows hyperbolæ. Then when γ is parallel to the trace of the axial plane, the ellipses appear to expand for positive crystals and to contract for negative crystals. When γ is perpendicular to the trace of the axial plane, the ellipses contract for positive crystals and expand for negative crystals.

A section of a biaxial crystal normal to an optic axis shows a series of concentric rings crossed by a dark bar which revolves in an opposite direction from the rotation of the stage.

The axial angle of a biaxial crystal may be measured by means of an axial angle apparatus, which is practically a reflection goniometer plus Nicol prisms. If a suitable crystal is mounted, so that it can be rotated around its β direction as an axis, between horizontal crossed nicols, arranged so that the interference figure shows hyperbolæ, the apparent axial angle can be determined by reading the circle when the vertices of the hyperbolæ are tangent to the cross-wires. Figure 361 represents a section of a biaxial crystal parallel at the axial plane. It will be seen that the angle measured is not $2V$, but another angle which is called $2E$ and related to it by the following equation: $\sin E = n\beta \sin V$. (n_β being the index of refraction in the direction of the optic axis). The value $2E$ is often recorded, as it is obtained directly.

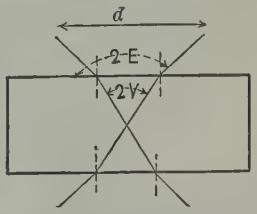


FIG. 361.—Section of a biaxial crystal to show the relation between true and apparent axial angles.

Another, but less accurate, method of measuring the axial angle is based upon the fact that the distance apart of the vertices (d in Fig. 361) of the hyperbolæ of an interference figure is proportional to the value of $2E$. This determination may be made by using a micrometer eye-piece in the microscope. The distance apart of the branches of the hyperbolæ of a substance with previously determined value of $2E$ is measured. This determines the constant C in the equation $\sin E = d/C$. So

for other crystals, if the same microscope and combination of lenses are used, the value E may be calculated from the measurement of d and substitution of C in the above formula.

13. OPTICAL PROPERTIES OF TWIN-CRYSTALS

One-half of a twin-crystal has the same position with respect to the other half that it would have if it were rotated 180° about an axis from its original position. From this it can be seen that the extinction angles in two halves of a twin-crystal are equal, but opposite in sign, if the section is cut normal to the twin-plane. Thus in a cleavage of a gypsum twin the extinction directions are inclined to each other. Consequently if examined between crossed nicols, one-half of such a crystal is dark, while the other half is light (see Fig. 362). On rotation, the light and dark parts interchange.

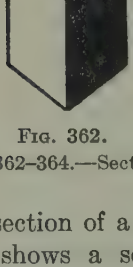


FIG. 362.

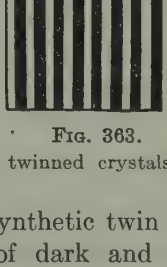


FIG. 363.

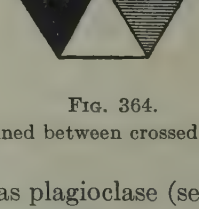


FIG. 364.

FIGS. 362–364.—Sections of twinned crystals examined between crossed nicols.

A section of a polysynthetic twin such as plagioclase (see Fig. 363) shows a series of dark and light bands; the extinction directions in alternate bands are parallel.

Many orthorhombic crystals such as aragonite are pseudo-hexagonal by twinning, and basal sections between crossed nicols are divided into six sectors like Fig. 364, opposite pairs of which extinguish together. Basal sections of aragonite, like Fig. 364, examined in convergent polarized light, show a biaxial interference figure in each sector but are arranged so that the axial

planes are parallel to the outline. An optical examination reveals the composite nature of many apparently simple crystals.

14. ABSORPTION AND PLEOCHROISM

The color of a transparent substance is due to the residual color of the spectrum left after the substance has absorbed a certain part of it. Many colored anisotropic crystals have the property of absorbing different amounts or kinds of light in different directions. **Absorption** has reference to the amount or intensity of light absorbed and hence may be tested in monochromatic light, while **pleochroism** refers to the kind of light absorbed and so necessarily must be tested in white light.

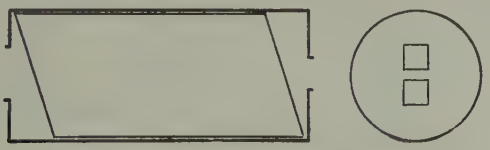


FIG. 365.—Dichroscope.

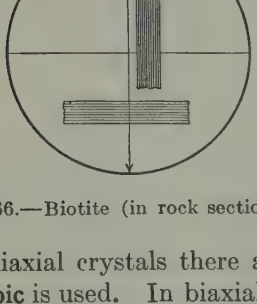
A prismatic crystal of epidote from the Sulzbachthal in Tyrol of suitable thickness will appear green in a certain position, while on revolving it 90° about its long axis it will appear brown. Few substances show such a marked change as this; at any rate it is not always possible to turn a crystal about and look through it in various directions.

The determination of pleochroism and absorption is made either by means of one nicol of a polarizing microscope, in which case minute crystals may be examined, or by means of the dichroscope when large crystals are available.

A **dichroscope** is simply a piece of Iceland spar set in a cylindrical frame that is provided with a small aperture at one end and either open or provided with a lens at the other end. Figure 365 is a diagrammatic representation of the dichroscope. When held up to the light the dichroscope shows two images of the aperture side by side, for the diameter of the aperture is made so that

the images do not overlap. If a pleochroic crystal is viewed through the dichroscope, two colored images are seen simultaneously. The reason for this is that in a doubly refracting calcite crystal we have two sets of light waves vibrating in planes at right angles to each other.

The color of some crystals, as we have seen, varies with the direction, but by using a Nicol prism we may observe the two colors successively, one when the vibration plane of the nicol is parallel to the length of the crystal, and one when perpendicular to the length of the crystal. These colors are called **axial colors.**



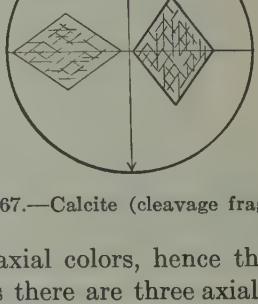


Fig. 366.—Biotite (in rock section). Fig. 367.—Calcite (cleavage fragments).

In uniaxial crystals there are two axial colors, hence the term **dichroic** is used. In biaxial crystals there are three axial colors, hence the term **trichroic.**

In order to determine the axial colors for particular directions it is necessary to ascertain the vibration plane of the lower nicol. For this purpose a rock-section containing biotite may be used. Biotite sections showing cleavage have very strong absorption. On revolving the section, the biotite becomes very dark every 180°. The cross-wire which is parallel to the cleavage traces of the biotite when it is darkest represents the vibration plane of the lower nicol as illustrated in Fig. 366. Here the arrow indicates the vibration plane.

If a rock-section containing biotite is not available, the test may be made by examining minute cleavage fragments of calcite

obtained by pounding to a coarse powder almost any kind of calcite. If mounted in oil of cloves or Canada balsam, the calcite rhombs have a marked relief when their long diagonals are parallel to the vibration plane of the lower nicol, and but slight relief when their short diagonals are parallel to this direction as represented in Fig. 367. The vibration direction of the lower nicol is indicated by the arrow.

Fragments of fibrous tourmaline may also be used for the same purpose. The prismatic fragments appear dark when their length is perpendicular to the vibration plane of the lower nicol. (See Fig. 330, p. 173.)

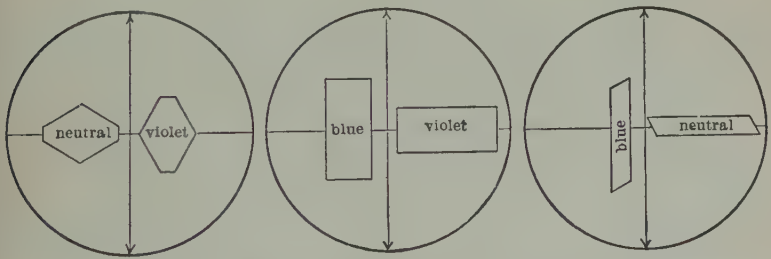


FIG. 368. FIG. 369. FIG. 370.

FIGS. 368–370.—Pleochroism of glaucophane.

The trichroism of a biaxial crystal is beautifully illustrated by the soda amphibole, glaucophane, as seen in thin rock-sections under the microscope. Three kinds of cross-sections may be distinguished as follows: pseudo-hexagonal (Fig. 368), stout rectangular (Fig. 369), and thin with oblique ends (Fig. 370). These sections are respectively almost perpendicular to the *c*-, *a*-, and *b*-axes. These sections when rotated on the stage of the microscope show respectively the following pairs of colors: neutral and violet, blue and violet, blue and neutral. It will be seen that the color for the *a*-axis is the neutral tint, for the mineral has this color when the *a*-axis is parallel to the vibration plane of the nicol (represented by the arrow). Similarly the violet is the

color for the b-axis, and blue for the c-axis. The three axial colors may be combined in an axial cross..

In glaucophane it has been found that $b = \beta$, and a (almost) = α, and c (almost) = γ. The absorption may be indicated by the following: $\gamma > \beta > \alpha$. This is called the **absorption scheme** and means that more light is absorbed in the γ or c-direction than in the β or b-direction, and more in the β or b-direction than in the α or a-direction. Sometimes Gothic letters are used instead of α, β, and γ.

15. SUGGESTED OUTLINE OF TESTS TO ILLUSTRATE THE OPTICAL PROPERTIES OF MINERALS

The following outline will serve as an introduction to the study of crystal optics. Most of the slides are made from cleavage flakes and fragments, but thin sections are necessary for some of the examples. The fragments are produced by pounding (not grinding) small chips of the mineral to coarse powder on an anvil or in an agate mortar. The largest fragments that will pass through a 100-mesh sieve are selected.

For temporary slides, clove oil is a convenient mounting medium. Permanent slides may be made by using a solution of Canada balsam in xylol. The xylol gradually evaporates.

On account of cleavage and structure a great many mineral fragments have a more or less characteristic shape. Those without cleavage are irregular (see Fig. 377).

Form.

Euhedral. Calamine crystal. (Measure angles and determine faces).
Subhedral — dolomite in sedimentary dolomitic limestone.
Anhedral—quartz in sandstone.

Cleavage fragments—(See Figs. 371–376.)

Triangular cleavage fragments—fluorite. (Fig. 371.)
Rectangular cleavage fragments—anhydrite. (Fig. 372.)
Rhombic cleavage fragments—calcite. (Fig. 373.)
Prismatic cleavage fragments—tremolite. (Fig. 374.)
Acicular cleavage fragments—wollastonite. (Fig. 375.)
Platy cleavage fragments (not previously included)—orthoclase. (Fig. 376.)
Irregular fragments—quartz. (Fig. 377.)

Inclusions.

Regularly arranged—labradorite, phlogopite.

Intergrowth—perthite (microcline with albite).

Alteration—olivine to antigorite.

Index of Refraction and Relief.

High relief, $n <$ clove oil—fluorite.
Low relief, $n <$ (about $=$) clove oil—orthoclase.
High relief, $n >$ clove oil—anhydrite.

FIG. 371.

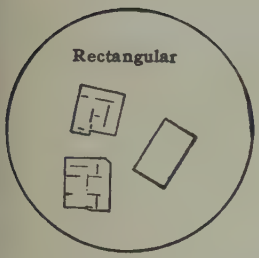


FIG. 372.

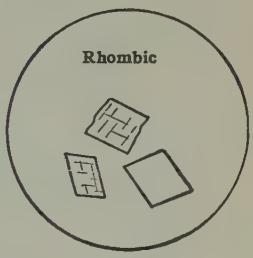


FIG. 373.

FIG. 374.

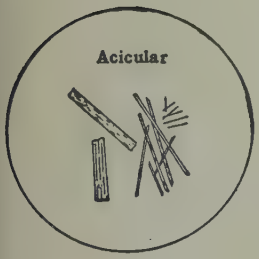


FIG. 375.

FIG. 376.

FIG. 377.

FIGS. 371–377.—Cleavage fragments as observed under compound microscope.

Pleochroism and Absorption.

Pink to red—pale blue to indigo—tourmaline.

Blue to purple—glaucophane.
Pink to pale green—hypersthene.

Relief varies with the direction—calcite.
(High relief when long diagonal of rhomb is parallel to the vibration plane of the lower nicol.)

Isotropic.
Amorphous—opal, volcanic glass.
Isometric—fluorite.

Anisotropic—anhydrite, quartz, apatite, etc.

Interference Colors.
Due to thin films—cleavage cracks in gypsum, calcite, or fluorite.
Effect of thickness—Gypsum wedge (made by shaving down a cleavage flake of gypsum.)
Effect of mineral { Low-order colors—apatite. / Bright colors—anhydrite. / High-order colors—calcite. }
Effect of orientation—Quartz in sandstone.

Extinction.
Parallel—wollastonite.
Symmetrical—calcite, dolomite.
Oblique, small extinction angle—hornblende, tremolite.
Oblique, large extinction angle—augite, diopside.

Elongation.
Parallel to faster ray—stilbite.
Parallel to slower ray—wollastonite.

Aggregate Polarization—chrysocolla.

Spherulitic Structure—chalcedony.

Optical Anomalies.
Amorphous, but doubly refracting—collophane.
Isometric mineral with double refraction—leucite.
Anomalous interference colors—vesuvianite, chlorite.

Twinning.
Simple—gypsum.
Polysynthetic—plagioclase.
Crossed—microcline.

Interference Figures.
Uniaxial positive.
Brucite, cleavage; quartz (basal section).
Uniaxial negative.
Calcite, basal parting; wulfenite, tabular crystal.
Biaxial positive, small axial angle.
Chlorite, cleavage.

Biaxial positive, large axial angle.
Topaz, cleavage.
Biaxial negative, small axial angle.
Phlogopite, cleavage.
Biaxial negative, large axial angle.
Muscovite, cleavage.
Biaxial, normal to optic axis, shows axial bar.
Epidote, (001) cleavage; diopside (001) parting.

Optical Orientation.—Muscovite crystal (determine position of α, β, and γ with respect to crystallographic axes a, b, and c).

16. LIST OF MINERALS ARRANGED ACCORDING TO INDICES OF REFRACTION

An arrow after a mineral name indicates that the mineral is doubly refracting. If the arrow points downward, the lower value (n_α) is the one given, and the highest value (n_γ) may be found in a place further on in the list. Other possible values lie between these two extremes.

The fact that no arrow is placed after a mineral name means that the mineral is either optically isotropic (amorphous or isometric) or has such a weak double refraction (less than 0.01) that the extreme values are included within a single division. Some amorphous and isometric minerals are variable in composition and so may be found in two or more divisions.

<1.45
Cryolite
FLUORITE
Ice
Nitratine ↓
1.45
OPAL
1.46
Carnallite ↓
CHRYSOCOLLA ↓
1.47
Natrolite ↓
Tridymite
1.48
Analcite
CALCITE ↓
Carnallite ↑
Chabazite
Cristobalite
Natrolite ↑
Sodalite
1.49
Heulandite
Kainite ↓
Stilbite
Sylvite
1.50
DOLOMITE ↓
Lazurite
Leucite
Ulexite ↓
1.51
Adularia ↓
Chalcanthite ↓
ORTHOCLASE ↓
Ulexite ↑
1.52
Adularia ↑
GYPSUM
Hydromagnesite ↓
Kainite ↑
Magnesite ↓
Microcline
ORTHOCLASE ↑
Strontianite ↓

Witherite ↓

1.53
Albite
Apophyllite
Aragonite ↓
CHALCEDONY ↓
Gibbsite ↓
Nepheline ↓

1.54
Chalcanthite ↓
CHALCEDONY ↑
Chrysotile ↓
HALITE
Hydromagnesite ↑
Oligoclase
Nepheline ↑
QUARTZ ↓
TALC ↓

1.55
Andesine
Chrysotile ↑
Gibbsite ↑
Halloysite
QUARTZ ↑
Scapolite ↓

1.56
ANTIGORITE ↓
Beryl
Brucite ↓
CHRYSOCOLLA ↑
Kaolinite
Labradorite
Lepidolite ↓
MUSCOVITE ↓
Phlogopite ↓
Sericite ↓

1.57
ANHYDRITE ↓
Anorthite ↓
ANTIGORITE ↑
BIOTITE ↓
Bytownite
CLIACHITE
Pyrophyllite
Vivianite ↓

1.58
Anorthite ↑
Brucite ↑
CHLORITE
Colemanite ↓
COLLOPHANE
Garnierite
Nitratine ↑
Pyrophyllite
TALC ↑

1.59
CHLORITE
COLLOPHANE
Lepidolite ↑
MUSCOVITE ↑
Scapolite ↑
Sericite ↑

1.60
Chondrodite ↓
COLLOPHANE
Rhodochrosite ↓
Phlogopite ↑

1.61
ANHYDRITE ↑
CALAMINE
Colemanite ↑
COLLOPHANE
Dahllite ↓
Prehnite ↓
SMITHSONITE ↓
Topaz ↓
Tremolite ↓
Turquois ↓

1.62
Celestite
COLLOPHANE
Dahllite ↑
Datolite ↓
Glaucophane ↓
Topaz ↑
Vivianite ↑
Wollastonite ↓

1.63
Andalusite
Anthophyllite ↓
BARITE ↓
BIOTITE ↑
CALAMINE ↑
Chondrodite ↑
Celestite ↑
Forsterite ↓
HORNBLENDE ↓
SIDERITE ↓
TOURMALINE ↓
Tremolite ↑
Wollastonite ↑

1.64
APATITE
BARITE ↑
Glaucophane ↑
Prehnite ↑

1.65
Anthophyllite ↑
CALCITE ↑
HORNBLENDE ↑
MALACHITE ↓
Spodumene ↓
TOURMALINE ↑
Turquois ↑

1.66
Datolite ↑
Enstatite ↓
OLIVINE ↓
Sillimanite ↑

1.67
Axinite
Diopside ↓
Enstatite ↑
Forsterite ↑
Spodumene ↑
Strontianite ↑
Witherite ↑

1.68
Aragonite ↑
DOLOMITE ↑
Sillimanite ↑

1.69
Hypersthene ↓
OLIVINE ↑
Willemite ↓

1.70
Diopside ↑
Hypersthene ↑
Willemite ↑

1.71
Augite ↓
Clinozoisite ↓
Kyanite ↓
Magnesite ↑

1.72
Clinozoisite ↑
Kyanite ↑
Rhodonite ↓
Spinel
Vesuvianite

1.73
Augite ↑
Brochantite ↓
EPIDOTE ↓
Grossularite
Rhodonite ↑
Staurolite ↓

1.74
(Methylene Iodid)
Anglesite
Azurite
Brochantite ↑
Carnotite
CASSITERITE
Cerargyrite
CERUSSITE
CHROMITE
CINNABAR
CORUNDUM
Cuprite
~~Diamond~~ See p. 214
EPIDOTE ↑
Goethite
GARNET
Hausmannite
HEMATITE
Jarosite
LIMONITE
MALACHITE ↑
Mimetite
Pitchblende
Polybasite
Pyrargyrite
Pyromorphite
Rhodochrosite ↑
Rutile
Scheelite
SIDERITE ↑
SMITHSONITE ↑
SPHALERITE
Staurolite ↑
SULFUR
Titanite
Turyite
Vanadinite
Wulfenite
Zircon

MINERALS

1. ELEMENTS.
2. SULFIDS.
3. SULFO-SALTS.
4. HALOIDS.
5. OXIDS.
6. ALUMINATES, FERRITES, ETC.
7. HYDROXIDS.
8. CARBONATES.
9. PHOSPHATES, NITRATES, BORATES, ETC.
10. SULFATES.
11. TUNGSTATES AND MOLYBDATES.
12. SILICATES.

MINERALOIDS
(GLASS AND HYDROCARBONS)

PART II

THE DESCRIPTION OF IMPORTANT MINERALS AND MINERALOIDS

Introductory

About a thousand or so distinct kinds of minerals or mineral species are recognized by the mineralogist. Most of these are very rare, many of them being found only at the single, original locality in which they were discovered. In this book 175 minerals are considered. These include all the common minerals, most of those of economic importance, and a few others which are added so as to give the student a comprehensive view of the mineral kingdom as a whole. The student may occasionally encounter a mineral not included in the list of 175 and the larger reference books such as Dana's *System* and Hintze's *Handbuch* must be consulted. There is also a possibility of finding a new mineral, but the chance is very remote for *bona fide* new minerals are being found and described at the rate of only about ten or so a year by mineralogists the world over.

By *mineral species* we mean all specimens with essentially the same chemical composition (some variation must be allowed as stated on page 13) and the same crystal form. Each mineral species has a distinctive name in addition to the chemical name of the substance of which it is composed. The name connotes certain physical properties in addition to chemical composition, for polymorphous modifications and amorphous equivalents are recognized as distinct minerals.

Most mineral names end in *-ite*. This custom has its origin in the practice of the Greeks and Romans of adding the suffix *-ites* or *-itis* (originally from the Greek *lithos*, a stone) to a word which was descriptive of the mineral, or indicated its use or the locality in which it was found. Other endings used especially

by Haüy are *-ane*, *-ase*, *-ene*, *-ine*, *-ose*, and *-ote*. Names in use before the custom of using the termination *ite* was adopted are quartz, opal, topaz, garnet, mica, diamond, galena, beryl, gypsum, zircon, and hornblende. It seems fortunate that we have some variety in our mineralogical nomenclature especially since the termination *-ite* has been used for rock names (granite, syenite, etc.) and for artificial compounds (aloxite, quercite, etc.).

Dana in 1837 used a binomial nomenclature for minerals like that at present used for plants and animals. Thus the genus *Baralus* included *Baralus ponderosus* (*barite*), *B. prismaticus* (celestite), *B. fusilis* (witherite), and *B. rubefaciens* (strontianite). The classification used then was based upon external characters or physical properties. This gradually gave way to the chemical classification of Berzelius and the Swedish chemists.

The modern chemical classification is one in which the minerals are arranged according to the acid radical. The principal classes of minerals are: elements, sulfids, sulfo-salts, haloids, oxids, hydroxids, carbonates, phosphates, nitrates, borates, sulfates, tungstates, and silicates. Within each of these divisions the minerals are arranged as far as possible in isomorphous groups. Thus calcite ($CaCO_3$), dolomite ($CaMg[CO_3]_2$), magnesite ($MgCO_3$), siderite ($FeCO_3$), rhodochrosite ($MnCO_3$), and smithsonite ($ZnCO_3$) are included in the calcite group of rhombohedral carbonates, for they crystallize in the hexagonal system and have rhombohedral cleavage and similar optical properties. Aragonite ($CaCO_3$) and cerussite ($PbCO_3$) together with the carbonates of strontium and barium constitute another group of orthorhombic carbonates, while malachite [$Cu_2(OH)_2CO_3$] and azurite [$Cu(OH)_2(CO_3)_2$] and hydromagnesite [$Mg_4(OH)_2(CO_3)_3 \cdot 3H_2O$] must be considered separately because they are basic carbonates unlike in crystal form and physical properties.

Certain naturally occurring homogeneous substances not definite enough in chemical composition to be called minerals are considered under the term **mineraloid.** They include volcanic glass and the hydrocarbons.

1. ELEMENTS

A. Non-metals

Diamond	C
GRAPHITE	C
SULFUR	S

B. Metals

GOLD	Au
SILVER	Ag
COPPER	Cu
Platinum	Pt
Iron	Fe

Of the eighty or more known elements only about twenty occur uncombined as minerals, if we leave out of consideration the free gases of the atmosphere. The elements occurring free and uncombined are: carbon, sulphur, selenium, tellurium, phosphorus, arsenic, antimony, bismuth mercury, copper, silver, gold, lead, iron, palladium, iridium, osmium, tantalum, and tin. From a chemical standpoint the elements may be divided into two classes: the metals and the non-metals. The metals include such elements as copper, silver, gold, lead, iron, and platinum. Some of these occur as alloys such as electrum (Au,Ag), amalgam (Ag,Hg), nickel-iron (Fe,Ni), and iridosmine, (Ir,Os). The non-metals include such elements as oxygen, hydrogen, nitrogen, phosphorus, carbon, and sulfur. Arsenic, antimony, and bismuth are intermediate in their properties between metals and non-metals and are usually called semi-metals or metalloids.

Diamond, C

Form. Diamond is practically always found in small loose crystals with rounded faces and curved edges. It crystallizes in the isometric system, probably in the hexoctahedral class. Though many of the isometric forms have been observed, the

only common well-defined one is the octahedron. Figure 378 represents a typical crystal with grooved edges and triangular markings. Spinel twins of diamond are rather common.

The internal structure of diamond determined by X-ray analysis is like that of sphalerite (Fig. 298, p. 144) except that all the atoms are carbon atoms.

Cleavage. Perfect octahedral. This fact enables the diamond-cutter to save considerable work.

H. = 10 (the hardest known substance).

Color. Diamond is usually colorless or faintly colored, though brilliantly colored blue, green, and red stones are known. One variety known as *carbonado* is black and opaque.

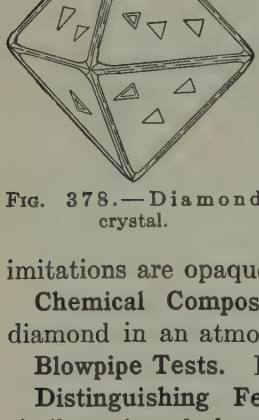


FIG. 378.—Diamond crystal.

Luster. The luster is the brilliant luster known as adamantine. The rough uncut crystals have a peculiar greasy appearance.

Optical Properties. The index of refraction is very high ($n = 2.4175$ for sodium light) which accounts for its brilliancy. The "fire" of the diamond is accounted for by its strong dispersion; the index of refraction for the red end of the spectrum is 2.402, while for the violet end it is 2.465. Diamonds are transparent to X-rays, while imitations are opaque.

Chemical Composition. Pure carbon. Upon heating the diamond in an atmosphere of oxygen it is converted into CO_2.

Blowpipe Tests. Infusible. Insoluble in acids.

Distinguishing Features. Diamond is distinguished from similar minerals by its superior hardness, its adamantine luster, and its comparatively high specific gravity.

The peculiar rounded crystals with an apparently oiled surface are unlike those of any other mineral.

Uses. On account of its great hardness, brilliancy, and rarity, diamond stands as the gem mineral, *par excellence*. Among the famous historic diamonds are the Kohinoor, 186 carats; the

Regent, 137 carats; the Star of the South, 254 carats; the Imperial, 457 carats; and the Excelsior, 969 carats. Of colored diamonds the most famous are the Tiffany (orange-yellow), the Hope (greenish-blue), the Dresden (bluish-green), and the Paul I. (ruby-red). The largest diamond on record is the Cullinan (since named the Star of Africa) found in 1905 at the Premier mine in the Transvaal. This diamond weighed 3106 metric carats (621.2 grams or about 1⅓ pounds avoirdupois).

Diamonds are also used as an abrasive in cutting and polishing precious stones, glass, and other materials. The center of the diamond cutting industry is Amsterdam.

Several mines within an area of ten square miles at Kimberley, South Africa, have furnished the world's principal supply of diamonds since their discovery in 1867.

A black, opaque, non-cleavable variety of diamond is used for diamond drills. It is found only in Bahia, Brazil, and is known as *carbonado* or "black diamond."

Occurrence. 1. In volcanic necks and dikes of a rock known as kimberlite (locally called "blue-ground"). Kimberlite is an altered peridotite composed of fragments of pyrope, pyroxene, biotite, olivine, etc., in a matrix of serpentine. The origin of the diamond is in doubt, but many believe it to be of igneous origin.

Diamonds have recently been found in a peridotite dike in Pike County, Arkansas. The stones are small in size but of very good quality.

2. In alluvial degosits associated with heavy minerals. Among these localities may be mentioned southern India, (where diamonds were first found), the states of Bahia and Minas Geraes, Brazil (one locality is known as Diamantina), and scattered localities throughout the United States. In the Great Lakes region, diamonds are found in glacial drift. In California small diamonds have frequently been found in sluice-boxes along with gold.

3. In the chromite of serpentinized dunite in the Tulameen

district, British Columbia, minute diamonds have recently been found.

4. In meteorites from Canon Diablo (Arizona), minute diamonds have been found. Moissanite, SiC, the same as the artificial carborundum, is also found there. A peridotite meteorite which fell at Novo-Urei, Russia, in 1886 also contained diamonds.

Moissan obtained small diamonds by cooling in water a block of soft iron saturated with carbon.

GRAPHITE, C

Form. Graphite occurs occasionally in six-sided tabular crystals, but more often in foliated masses, minute disseminated scales, or earthy lumps.

Cleavage. Cleavage in one direction.

H = 1 to 2. **Sp. gr.** 2.1±.

Color. Dark gray to black. Luster, metallic. Streak, gray. Opaque even in thinnest fragments. Sectile.

Chemical Composition. Graphite is a modification of carbon. It grades from pure carbon to earthy varieties which yield a large amount of ash on combustion.

Blowpipe Tests. The tests for graphite are largely negative on account of its refractory nature. Infusible. Insoluble in acids.

Distinguishing Features. Graphite resembles molybdenite but is distinguished by its lower specific gravity, negative $NaPO_3$ bead test, negative sulfid test, and difference in streak on glazed porcelain or glazed paper. (Molybdenite has a greenish gray streak.)

It is distinguished from hematite by its streak and lower specific gravity, from magnetite by its inferior hardness and failure to be attracted by a magnet, and from hydrocarbons by its non-volatility in the closed tube.

Uses. Graphite is used in the manufacture of lead pencils (varying hardness is due to admixed clay), lubricants for machinery, refractory crucibles, and electrical supplies. Austria and Ceylon are the chief producers.

Artificial graphite is now made from anthracite in electric furnaces at Niagara Falls.

Occurrence. 1. In crystalline limestones, doubtless formed by the recrystallization of the organic matter of sedimentary limestones. Franklin, New Jersey.

2. In schists and gneisses, often as an essential constituent. Hague, New York.

3. In veins, in granites and granulites, which proves that its origin may be independent of previous life. Ceylon.

4. In coal-beds, the coal is often converted into graphite near the contact with igneous intrusions.

5. In meteorites. Paramorphs of graphite after diamond, called cliftonite, are also found in meteorites. (On heating diamond out of contact with air it is converted into graphite).

SULFUR, S

Form. Sulfur occurs in crystals, incrustations, disseminations, and compact masses. The crystals are good examples of the orthorhombic system. Usual forms: $p\{111\}$, $c\{001\}$, $n\{011\}$, and $s\{113\}$. The habit is usually pyramidal, with $\{111\}$ as the dominant form. Interfacial angles: $pp(111 : 1\bar{1}1) = 94° 52'$, $cp(001 : 111) = 71° 40'$, $cs(001 : 113) = 45° 10'$, $cn(001 : 011) = 62° 17'$. Figure 379 is the common type of crystal.

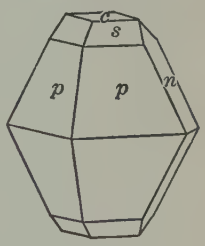


FIG. 379.—Sulfur crystal.

H. = 1½ to 2½. **Sp. gr.** 2.07±.

Color. Yellow, sometimes with orange, brown, or green tinge.

Luster. Resinous to adamantine.

Optical Properties. $n_\gamma(2.24) - n_\alpha(1.95) = 0.29$. Fragments are irregular with high-order interference colors.

Chemical Composition. Sulfur, often with such impurities as clay and asphaltum. Some varieties contain selenium.

Blowpipe Tests. Fuses easily (114° C.) and burns with a blue flame, giving off sulfur dioxid. If impure, a residue is left.

Insoluble in acids. Soluble in carbon bisulfid and on evaporation minute crystals are formed.

Distinguishing Features. Sulfur is not apt to be confused with any other mineral. It may, however, be overlooked when occurring as an impregnation of tuff or clay, as the color is apt to be gray instead of yellow. This material will burn and leave a residue.

Uses. Sulfur is used in the manufacture of gunpowder, matches, for vulcanizing rubber, and for the production of sulfur dioxid, which is used in paper manufacturing and bleaching. It was formerly used in the manufacture of sulfuric acid, but that is now made from pyrite. The island of Sicily and southwestern Louisiana are the principal sources of sulfur. At the latter locality the sulfur is obtained by dissolving it in superheated steam and pumping the solution to the surface.

Occurrence. 1. As a sublimate in the crevices around volcanoes (called solfataras) or as an impregnation of tuffs. Formed by the incomplete oxidation of hydrogen sulfid. $2H_2S + O_2 = 2\,S + 2H_2O$.

2. In sedimentary rocks (limestones, travertine, and marl) with gypsum, and occasionally with celestite. Girgenti, Sicily.

3. As a decomposition product of sulfids such as galena, stibnite, sphalerite, and pyrite.

4. Formed by some bacteria and algæ in sulfate-bearing waters.

Sulfur furnishes one of the best examples of polymorphism. The orthorhombic modification, known as α-sulfur, is the one that occurs so extensively in nature. The monoclinic modification (β-sulfur) formed when sulfur solidifies from fusion has been noted in nature several times, but it rapidly changes to the orthorhombic form on standing.

GOLD, Au

Form. Though usually finely disseminated through containing rock and only apparent on assaying, gold also occurs in rolled

grains and scales, occasionally in large nuggets, and rarely in crystals and imperfect crystal aggregates. Like many of the metals, gold crystallizes in the isometric system, the octahedron being the only common form. Sheets of gold (leaf-gold) with raised triangular markings are not uncommon.

H. = 2½ to 3. **Sp. gr.** = 15 to 19 (according to purity). Pure gold has a specific gravity of 19.3.

Color. Deep to pale yellow. The pale yellow variety containing over 20 per cent. silver is known as *electrum*. Luster, metallic. Very malleable.

Chemical Composition. Gold, always alloyed with more or less silver, sometimes also with Bi, Cu, Fe, Pd, and Rh. The purity of gold is expressed by the amount of gold in 1000 parts. For example, gold with 13 per cent. silver has a fineness of 870. The following analyses give an idea of the variation in the chemical composition.

	Au	Ag	Misc.	Sp. Gr.
South Australia	93.5	6.5	.....	18.8
Urals	87.4	12.1	Cu = 0.1	17.4
Peru	79.9	20.1	.....	16.6
Verespatak	66.4	33.2	SiO_2 = 0.4	15.0

Blowpipe Tests. Fusible at 3. With mercury forms an amalgam.

Soluble in aqua regia; the silver-bearing varieties leave a residue of AgCl.

Distinguishing Features. Pyrite and chalcopyrite are sometimes mistaken for gold but they are easily distinguished by their brittleness, lower specific gravity, and by the fact that they are soluble in nitric acid. Yellow, decomposed scales of mica are even more like gold in appearance, but a careful examination reveals their true nature.

Uses. Native gold is the source of most of the gold of commerce, but some is derived from the gold tellurid (Calaverite).

In order of their production the countries are: Transvaal, United States, Australia, Russia, and Canada. The States in order are: California, Colorado, Alaska, Nevada, and South Dakota.

Occurrence. 1. In quartz veins along with pyrite, chalcopyrite, galena, sphalerite, arsenopyrite, etc.

2. In placers along streams (ancient river-channels in some cases) associated with heavy minerals such as magnetite, ilmenite, garnet, zircon, platinum, etc. Prominent localities are Alaska, California, Brazil, Colombia, Urals, and Australia.

3. In the quartzite conglomerate ("banket") on the Rand, Transvaal, South Africa. The origin of the gold is in doubt.

4. In the gossan or oxidized zone as a secondary mineral or mechanically released. At Cripple Creek, gold pseudomorphous after calaverite is found in the oxidized zone.

SILVER, Ag

Form. The characteristic occurrences of silver are in wire form, thin sheets, skeleton crystals, dendritic groups, and masses. The cube is the only common crystal form, but the crystals are very small.

H. = 2½. **Sp. gr.** 10.5±.

Color. Tin-white to pale yellow, but is usually dull and tarnished. Luster, metallic. Malleable.

Chemical Composition. Silver, often with some gold and copper.

Blowpipe Tests. Easily fusible (2) to a malleable button.

Soluble in HNO_3. HCl gives a white precipitate (AgCl), which turns violet on standing and is soluble in NH_4OH.

Distinguishing Features. Silver resembles some of the other native metals but is easily distinguished by the color of a freshly cut surface.

Uses. Native silver is the source of some silver, although most of the supply is derived from the sulfid and sulfo-salts. The Cobalt (Ontario) district now furnishes about one-tenth of the

world's supply of silver, the silver being largely in the form of the native metal.

Occurrence. 1. In veins associated with cobalt and nickel minerals. Cobalt, Ontario, is a prominent locality.

2. In veins with argentite, pyrargyrite, polybasite, stephanite, etc., and usually the last mineral to be formed and probably by ascending solutions.

3. In the gossan or oxidized zone, often associated with cerussite and limonite, and doubtless formed by descending solutions. Leadville, Colorado, and the Coeur d'Alene district in Idaho are prominent localities.

In contrast with gold, silver is practically never found in placers.

COPPER, Cu

Form. Copper is found in small disseminated grains, in sheets, and occasionally in large masses. Copper crystallizes in the isometric system, but the crystals are usually distorted and associated in dendritic groups. The forms {100}, {111}, {110}, and {210} can sometimes be made out.

H. = 2½. **Sp. gr.** 8.8±.

Color. Copper-red, often tarnished and also encrusted with alteration products such as cuprite and malachite. Metallic luster. Malleable.

Chemical Composition. Copper, often with a little silver.

Blowpipe Tests. Fusible (3) to a malleable globule.

Soluble in dilute HNO_3 to a green solution with the evolution of NO_2. With an excess of NH_4OH, the nitric acid gives a deep blue coloration solution.

Distinguishing Features. The color of freshly cut copper is distinctive.

Uses. Native copper is an important source of copper in but one locality (Upper Peninsula of Michigan), where immense quantities of copper ore are produced from very low grade ores.

Occurrence. In the oxidized zone of many copper mines formed by the reduction of copper compounds in solution, which in turn were formed by the oxidation of chalcopyrite.

2. In amygdaloidal diabases and basalts associated with calcite, datolite, prehnite, epidote, zeolites, and sometimes with silver. The Upper Peninsula of Michigan is the type locality.

Platinum, Pt

Form. Platinum is found in rounded grains, scales, and irregular lumps. Cubic crystals have been found but are exceedingly rare.

H. = 4½. **Sp. gr.** 15–19 (21, if pure).

Color. Light steel gray. Luster metallic. Malleable. Some varieties are magnetic because of the high iron content.

Chemical Composition. Platinum, often alloyed with iron and metals of the platinum group (Ir, Os, Pd, Rh).

	Pt	Fe	Pd	Rh	Ir	Os	Cu	
Urals	80.9	2.3	1.6	11.1	tr	...	1.0	S = 0.8
Colombia	84.8	8.3	1.0	2.1	1.0	1.0	0.6	
California	79.8	9.4	0.3	3.4	4.3	1.1	0.3	

Blowpipe Tests. Infusible.

Soluble in aqua regia. From this solution KCl precipitates K_2PtCl_6, a yellow crystalline powder composed of minute octahedra.

Distinguishing Features. Platinum is recognized by its high specific gravity, and its refractory nature.

Uses. Platinum is used largely for chemical apparatus and in jewelry, but also for some industrial purposes. Native platinum is the only source of platinum. The Ural Mountains furnish practically the entire supply.

Occurrence. 1. In placer deposits along with gold, magnetite, ilmenite, zircon, diamond, etc. Prominent localities are the

Ural Mountains, Colombia, British Columbia, northern California, and southern Oregon.

2. In peridotites or dunites with chromite, olivine, and serpentine. These rocks are the original source of the platinum of placers. Urals and British Columbia.

Iron, Fe to (Fe,Ni)

Form. Iron is found in compact or spongiform masses and in disseminated grains. Iron crystallizes in the isometric system, but distinct crystals are exceedingly rare. Many meteoric irons have an octahedral structure which is revealed by etching a polished surface with nitric acid, and is due to varying solubility of several different alloys of iron and nickel.

H. = 4½. **Sp. gr.** 7.5±.

Color. Steel-gray to iron-black, often covered with iron-rust. Luster, metallic. Malleable. Attracted by the magnet.

Chemical Composition. Iron, usually alloyed with nickel. It usually contains small amounts of cobalt, copper carbon, sulfur, phosphorus, etc.

	Fe	Ni	Co	Cu	S	Mn	C	Silicates, Insol.
Terrestrial iron, Greenland.....	91.7	1.7	0.5	0.1	0.1	...	1.4	3.9
Meteoric iron, Siberia.....	88.4	10.7	0.5	0.1	tr.	0.1	0.1	0.5

Blowpipe Tests. Infusible. Amber borax bead in O.F., bottle green in R.F.

Soluble in HCl with the evolution of hydrogen. Iron becomes copper-coated in a solution of copper sulfate.

Distinguishing Features. Iron is recognized by its oxidized surface and bright metallic interior.

Occurrence. 1. In meteorites, either as the main constituent (iron meteorites) or associated with silicates such as olivine (iron-stone meteorites).

2. Terrestrial iron is usually formed by the reduction of iron compounds. The only prominent locality is Disco Island off the west coast of Greenland, where large masses are found in a basalt. This iron constitutes a natural steel as it contains the requisite amount of carbon and shows the microscopic structure characteristic of steel. The basalt is associated with coal beds and the coal has doubtless served as a reducing agent of the iron in the basaltic magma.

2. SULFIDS

STIBNITE	Sb_2S_3
Bismuthinite,	Bi_2S_3
Molybdenite,	MoS_2
Argentite,	Ag_2S
GALENA,	PbS
CHALCOCITE,	Cu_2S
SPHALERITE,	ZnS
Pentlandite	(Fe,Ni)S
CINNABAR,	HgS
Covellite,	CuS
PYRRHOTITE,	$FeS(S)_x$
PYRITE,	FeS_2
Smaltite,	$(Co,Ni)As_2$
Marcasite	FeS_2
ARSENOPYRITE,	FeAsS
Calaverite,	$AuTe_2$

The sulfids and their analogues, the selenids, tellurids, arsenids, etc., are derivatives of H_2S, H_2Se, H_2Te, H_2As, etc. They may be considered as salts of these acids or as sulfanhydrids of sulfo-salts, just as the oxids are anhydrids of the oxy-salts. They are mostly sulfids of the heavy metals. The sulfids may be divided into two classes: (1) the sulfids of the semi-metals, and (2) the sulfids of the metals. Minerals under each of these are arranged according to increasing number of sulfur atoms in the formula. Prominent isomorphous groups are indicated by brackets.

STIBNITE, Sb_2S_3

Form. Stibnite is found in prismatic or acicular crystals, in columnar or bladed aggregates, and in granular masses. Crystals are orthorhombic (bipyramidal class). The habit is long

prismatic with {110} as the dominant form ($110:1\bar{1}0 = 89° 34'$). Crystals are often highly modified and always vertically striated.

Cleavage. Perfect in one direction parallel to the side pinacoid (010). It may also have parting parallel to (001) which is manifested in cross lines on the cleavage surfaces.

H. = 2. **Sp. gr.** 4.5±.

Color. Lead gray. Luster, brilliant metallic on fresh surface. Streak, lead gray.

Chemical Composition. Antimony sulfid, Sb_2S_3; (Sb = 71.4 per cent.).

Blowpipe Tests. On charcoal easily fusible (1), gives a pale greenish-blue flame, dense white fumes, and a white sublimate close to the assay. In the open tube gives SO_2 and a white nonvolatile sublimate (Sb_2O_4) on the under side of the tube. In the closed tube gives a dark red sublimate of antimony oxysulfid (Sb_2S_2O).

Decomposed by HNO_3 with the separation of a white precipitate of metantimonic acid ($HSbO_3$).

Distinguishing Features. Stibnite differs from similar minerals in its perfect cleavage in one direction, and its easy fusibility. (It can be fused in the flame of a match). It is often coated with pale yellow stibiconite, a product of oxidation.

Uses. Stibnite is the principal source of antimony which is used extensively in the manufacture of various alloys. Some of these alloys, such as type-metal, are made directly from antimonial lead ores. China is the principal producer of stibnite.

Occurrence. 1. As a vein mineral often associated with pyrite, sphalerite, galena, cinnabar, and realgar in a gangue of quartz, barite, or calcite. Prominent localities for specimens of stibnite are Felsöbanya, Hungary, and Shikoku, Japan. At the latter locality magnificent crystals over a foot in length are found.

Bismuthinite, Bi_2S_3

Form. Bismuthinite is isomorphous with stibnite, and greatly resembles it.

Cleavage. In one direction parallel to the length.

H. = 2. **Sp. gr.** 6.4±.

Color. Lead gray, often with a peculiar yellowish tarnish.

Chemical Composition. Bismuth sulfid, Bi_2S_3; (Bi = 81.2 per cent.). Some varieties contain Se.

Blowpipe Tests. Easily fusible (1), gives on charcoal a metallic button (malleable, but brittle on the edges) and a yellow coating. Heated with iodid flux on plaster it gives a purplish chocolate sublimate with underlying scarlet.

Soluble in HNO_3. On diluting the solution with water a white precipitate is formed.

Distinguishing Features. Resembles stibnite and is only distinguished from it by blowpipe or chemical tests.

Uses. Bismuthinite is probably the most important bismuth mineral. Bolivia is the chief producer.

Occurrence. 1. As a vein mineral associated with bismuth and chalcopyrite especially.

Molybdenite, MoS_2

Form. Molybdenite is usually found in foliated masses or in disseminated scales, and occasionally in hexagonal crystals of tabular habit.

Cleavage. In one direction parallel to {0001}.

H. = 1½. **Sp. gr.** 4.7±.

Color. Bluish lead gray. The streak on glazed porcelain or glazed paper (the thumb nail is a fair substitute) has a greenish tinge. Cleavage plates are flexible and sectile.

Chemical Composition. Molybdenum sulfid, MoS_2 (Mo = 60.0 per cent.).

Blowpipe Tests. Infusible. On charcoal gives a white sublimate which is copper red near the assay. Green $NaPO_3$ bead in R.F., colorless in O.F.

Decomposed by HNO_3 with the formation of a white sublimate (MoO_3) which is soluble in NH_4OH.

Distinguishing Features. Distinguished from graphite by higher specific gravity and streak on glazed paper.

Uses. Molybdenite is the chief source of molybdenum which is used as an alloy with steel. Australia is the leading producer of molybdenite.

Occurrence. 1. In pegmatites and surrounding rocks, especially granite.

2. In tin-stone veins with cassiterite, wolframite, topaz, etc.

3. In contact-metamorphic zones between limestones and granites associated with epidote, chalcopyrite, etc.

Argentite, Ag_2S

Form. Occurs massive, incrusting, more rarely in rough crystals. The crystals are isometric, the only common form being the cube. Cubes are often arranged in parallel position.

H. = 2½. **Sp. gr.** 7.3 ±.

Color. Dark lead gray, dull black on exposed surface. Luster, metallic. Very sectile.

Chemical Composition. Silver sulfid, Ag_2S; (Ag = 87.1 per cent.)

Blowpipe Tests. Easily fusible (1½). On charcoal yields a malleable button of silver.

Soluble in HNO_3 with the separation of S. HCl gives a white precipitate (AgCl) soluble in NH_4OH.

Distinguishing Features. Distinguished by its perfect sectility and metallic luster.

Uses. Argentite, the silver glance of the miner, is an important ore of silver on account of the high silver content.

Occurrence. As a vein mineral associated with other silver minerals, and pyrite, galena, sphalerite, etc. Freiberg, Saxony.

GALENA, PbS

Form. Galena occurs in well-formed crystals as well as in cleavable and granular masses. Crystals are isometric (hexoctahedral class). The usual forms are the cube {100}, the octahedron

{111}, more rarely the dodecahedron {110}, and the trisoctahedron {221}. The habit is usually cubic, cubo-octahedral, or octahedral, as shown by Figs. 380–384. Small octahedral crystals are sometimes found in parallel position on large cubic crystals.

Cleavage. Perfect cubic cleavage.

H. = 2½. **Sp. gr.** 7.5 ±.

Color. Lead gray, often tarnished. Metallic luster.

Chemical Composition. Lead sulfid, PbS (Pb = 86.6 per cent.) May contain zinc, silver, free sulfur, and other impurities. If the silver is chemically combined, it is present in amounts less than 0.1 per cent, according to Guild.

Blowpipe Tests. Easily fusible at 2, giving on charcoal a malleable button, a yellow sublimate (PbO) near the assay, and a white sublimate ($PbSO_4$) farther from the assay.

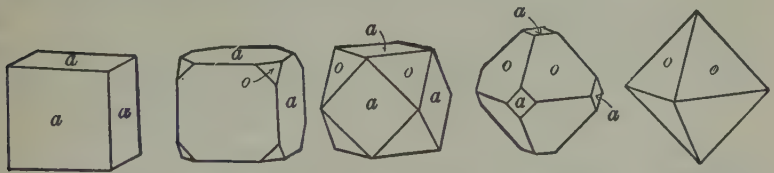


Fig. 380. Fig. 381. Fig. 382. Fig. 383. Fig. 384.

Figs. 380–384.—Galena crystals.

The silver may be obtained by cupellation (see p. 34).

Decomposed by HCl with the separation of $PbCl_2$, a white crystalline precipitate soluble in hot water. Decomposed by HNO_3 with the separation of S and $PbSO_4$.

Distinguishing Features. It is an easy mineral to recognize on account of its cleavage and high specific gravity.

Uses. Galena is the most important ore of lead; argentiferous galena is one of the most important silver ores. The silver is for the most part present as included silver minerals. Southeastern Missouri and the Coeur d'Alene district of Idaho are the most important sources of galena.

Occurrence. 1. In veins associated with sphalerite, chalcopyrite, pyrite, etc., often with barite or fluorite, a gangue mineral. In the north of England galena occurs with fluorite, barite, calcite, and sphalerite in veins in Sub-carboniferous limestone.

2. In sedimentary rocks such as limestones, shales, and sandstones often associated with sphalerite. In southeastern Missouri galena is disseminated through Ordovician limestone.

3. In contact-metamorphic zones with sphalerite.

CHALCOCITE, Cu_2S

Form. Usually fine-grained compact masses, rarely in pseudohexagonal orthorhombic crystals, which are sometimes twinned.

H. = 2½. **Sp. gr.** = 5.78.

Color. Dark lead-gray with black tarnish. Metallic luster. Chalcocite is sub-sectile (*i.e.*, it can be cut with a knife, but not so readily as argentite).

Chemical Composition. Cuprous sulfid, Cu_2S; (Cu = 79.8 per cent.). It may contain a little cupric sulfid in solid solution. A little iron is usually present, due to admixed bornite, chalcopyrite, or pyrite.

Blowpipe Tests. Fuses at 2. Unaltered in the closed tube. In the open tube gives the odor of SO_2. In R.F. on charcoal gives metallic copper.

Soluble in HNO_3 giving brown-red fumes, residue of S, and a green solution.

Distinguishing Features. A compact massive mineral, distinguished by its imperfect sectility, especially from tetrahedrite, which is very brittle.

Uses. Chalcocite is a valuable ore of copper on account of the high percentage of copper. At the Bonanza Mine, Kennecott, Alaska, enormous quantities of chalcocite ore running 70 per cent. copper are being mined. It is a prominent mineral in the ores at Butte, Montana, and also occurs in the disseminated "porphyry copper" ores in Arizona, Utah, and Nevada.

Occurrence. 1. As a product of downward secondary enrichment, formed at the expense of pyrite, chalcopyrite, or bornite. Bingham, Utah.

2. As a vein mineral associated with pyrite, chalcopyrite, bornite, and covellite and is often formed as a replacement of these minerals by ascending solutions. Butte, Montana.

On heating orthorhombic chalcocite (β-Cu_2S) to a temperature of 91°C or above, it changes to an isometric form (α-Cu_2S). Some specimens of chalcocite show structures on polished surfaces which prove them to be paramorphs of β-Cu_2S after α-Cu_2S. This makes it practically certain that some chalcocite has been formed by hydrothermal ascending solutions.

SPHALERITE, ZnS

Form. Sphalerite crystallizes in the hextetrahedral class of the isometric system. Crystals are usually distorted and difficult to decipher. The common habits are tetrahedral and dodecahedral; the usual forms are $a\{100\}$, $d\{110\}$, $o\{111\}$, $o_1\{1\bar{1}1\}$,

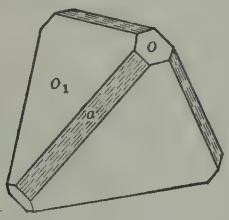


Fig. 385.

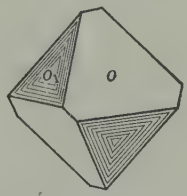


Fig. 386.

Figs. 385, 386.—Sphalerite crystals.

and $m\{311\}$. Figs. 385 and 386 represent typical crystals. Crystals are often twinned on the {111} face and twinning striations due to polysynthetic twinning on this face are sometimes observed.

The internal structure of sphalerite as determined by X-ray analysis (Bragg and Bragg) is shown in Fig. 298, p. 144.

Cleavage. Very prominent (dodecahedral at angles of 60°).

H. = 3½ to 4. **Sp. gr.** 4.0 ±.

Color. The color of sphalerite varies from white to black, depending upon the amount of iron present. The usual color is yellowish-brown or reddish-brown. The luster varies from adamantine to submetallic, and the streak from pale yellow in yellow varieties to dark brown in the black varieties.

Optical Properties. $n = 2.37$. Fragments are triangular, pale yellow to brown, and isotropic (dark between crossed nicols). The high index of refraction accounts for the adamantine luster.

Chemical Composition. Zinc sulfid, ZnS; (Zn = 67.0 per cent.). Usually contains iron (up to as high as 20 per cent.) which replaces zinc isomorphously, as shown in the formula (Zn,Fe)S. Cadmium is another common impurity present in part as a isomorphous replacement of zinc and in part as an associated cadmium sulfid (xanthochroite) occurring as an amorphous yellow incrustation on sphalerite. The rare elements indium and gallium were discovered in sphalerite. The following are typical analyses:

	Zn	Fe	S	Misc.
White: Franklin, New Jersey	67.5	....	32.2	Cd = tr
Yellow: Schemnitz, Hungary	65.2	0.5	32.8	Cd = 1.5
Brown: Roxbury, Connecticut	63.4	3.6	33.4	
Dark brown: Westphalia	58.2	8.2	33.4	Cu = 0.1; Pb = tr
Black: Felsöbanya, Hungary	50.0	15.4	33.3	Cd = 0.3; Pb = 1.0

Blowpipe Tests. Fusible with difficulty (5). On charcoal gives a white sublimate, which is yellow when hot. This sublimate heated intensely with cobalt nitrate solution gives a green color (cobalt zincate). The presence of cadmium is indicated by an iridescent coating on charcoal.

Soluble in HCl with the evolution of H_2S.

Distinguishing Features. The perfect cleavage together with the adamantine luster will distinguish sphalerite from all other common minerals. It somewhat resembles siderite and occasionally garnet.

Uses. Sphalerite is the most important ore of zinc. The Joplin district of southwest Missouri is the principal locality in this country.

Occurrence. 1. As a vein mineral associated with galena, chalcopyrite, pyrite, and other sulfids in a gangue of quartz, calcite, barite, fluorite, dolomite, etc.

2. As a replacing or accessory mineral in sedimentary rocks, especially limestones.

3. As a contact-metamorphic mineral. Magdalena mines, New Mexico.

Pentlandite (Fe,Ni)S

Form. A massive mineral very much like pyrrhotite in appearance.

Cleavage. Octahedral.

H. = 3½ to 4. **Sp. gr.** 4.8 ±.

Color. Bronze-yellow like pyrrhotite. Opaque, non-magnetic.

Chemical Composition. Iron and nickel sulfid (Fe,Ni)S. (Ni = 20 to 40 per cent.)

Blowpipe Tests. Easily fusible (at 2) to a magnetic globule which gives the bead tests for iron and nickel.

Soluble in nitric acid to a green solution. When made alkaline the solution gives a red ppt. with dimethylglyoxime.

Distinguishing Features. It very much resembles pyrrhotite but is distinguished by its octahedral cleavage (or parting) and by its non-magnetic character. On a polished surface containing pyrrhotite it is not affected by HCl, while the pyrrhotite is.

Uses. Pentlandite is the chief ore of nickel. It is extensively mined in the Sudbury district, Ontario, Canada where it occurs intimately associated with pyrrhotite and chalcopyrite. This district is the most important producer of nickel ore; its only rival is New Caledonia.

Occurrence. 1. As a magmatic sulfid associated with, and formed later than, pyrrhotite. Sudbury District, Ontario, Canada.

CINNABAR, HgS

Form. Cinnabar usually occurs disseminated through the rock and in massive and earthy forms. It may also occur in minute crystals in cavities. The crystals are hexagonal and of variable habit.

Cleavage. Perfect, often parallel to length of the crystal. Even in massive varieties reflections from minute cleavage planes usually may be seen with a lens.

H. = 2½. **Sp. gr.** 8.0 ±.

Color. Scarlet to dark red, sometimes black when impure. Luster, adamantine in typical specimens. Streak, vermilion.

Optical Properties. $n_\gamma(3.20) - n_a(2.85) = 0.35$. Fragments are red, and irregular with high order interference colors. The very high index of refraction accounts for the adamantine luster.

Chemical Composition. Mercuric sulfid, HgS; (Hg = 86.2 per cent.). Clay and organic matter are often present as impurities.

Blowpipe Tests. Volatile if pure. In the closed tube with dry sodium carbonate, cinnabar gives a sublimate of metallic mercury (little globules when rubbed with a wire).

Soluble in HNO_3.

Distinguishing Features. Cinnabar is distinguished from other red colored minerals by its high specific gravity, adamantine luster, and cleavage.

Uses. Practically the only ore of mercury. The principal producing localities are Almaden, in Spain, Idria, in Austria, New Almaden and New Idria in California.

Occurrence. 1. In deposits formed near the surface. The more common associated minerals are pyrite, marcasite, stibnite, and mercury. The gangue minerals are chalcedony, opal, barite, and calcite.

Covellite, CuS

Form. Tabular hexagonal crystals are rare; the mineral usually occurs as a dissemination or incrustation.

H. = 1½ to 2. **Sp. gr.** = 4.68.

Color. Deep indigo blue. sometimes almost black. Luster, metallic pearly to earthy.

Chemical Composition. Cupric sulfid, CuS; (Cu = 66.4 per cent.).

Blowpipe Tests. Fusible at 2½. In the closed tube gives a sublimate of sulfur (distinction from chalcocite). On charcoal burns with a blue flame, gives off SO_2, and leaves a residue of metallic copper.

Soluble in HNO_3 to a green solution.

Distinguishing Features. The dark blue color is distinctive for a metallic mineral.

Uses. One of the minor ores of copper. It is prominent in some of the Butte mines.

Occurrence. 1. A characteristic mineral of the zone of downward secondary sulfid enrichment. In occurs associated with chalcopyrite, bornite, and chalcocite.

2. In veins with other copper minerals and probably formed by ascending solutions. Butte, Montana.

PYRRHOTITE, $FeS(S)_x$

Form. Pyrrhotite is usually massive and without distinct cleavage, though it may have a platy structure. Pseudohexagonal orthorhombic crystals of tabular habit are known, but are very rare.

H. = 4. **Sp. gr.** 4.6±.

Color. Bronze-yellow. Luster, metallic. Attracted by the magnet but usually only slightly so.

Chemical Composition. Ferrous sulfid, usually with a little excess of sulfur present in solid solution and expressed by the formula $FeS(S)_x$. (Fe = 60–63.6 per cent.). It frequently contains nickel which is present as admixed pentlandite.

Blowpipe Tests. Fuses at 3 to a magnetic globule, gives fumes of SO_2. In the closed tube gives little or no sulfur (distinction from pyrite).

Soluble in HNO_3.

Distinguishing Features. The bronze color and slightly magnetic character of pyrrhotite are distinctive. It can be distinguished from pyrite by the fact that it is scratched by the knife.

Uses. The pyrrhotite itself has no special uses, but the intimately associated pentlandite which occurs with it at Sudbury, Canada, is the world's chief source of nickel.

Occurrence. 1. In plutonic basic igneous rocks, such as gabbros and norites, as a late magmatic mineral formed by the replacement of the silicate minerals.

2. In high-temperature veins and replacement deposits.

3. In contact-metamorphic deposits.

4. In meteorites. This variety, FeS, without an excess of sulfur, is known as troilite.

PYRITE GROUP—ISOMETRIC

Pyrite, FeS_2; smaltite, $CoAs_2$; chloanthite, $NiAs_2$; cobaltite, CoAsS; and gersdorffite, NiAsS, constitute an isomorphous group as they crystallize in the diploid class of the isometric system in cubes and pyritohedrons, and have a hardness of 5½ to 6½ and a specific gravity of 5 to 6.5. There are also intermediate compounds such as $(Co,Fe)As_2$, $(Ni,Fe)As_2$, and (Co,Fe)AsS. The general formula, then, can be written $(Fe,Co,Ni)(As,Sb,S)_2$.

PYRITE, FeS_2

Form. Pyrite is often well crystallized and furnishes the typical example of the diploid class of the isometric system. The most common forms are the cube $a\{100\}$, pyritohedron $e\{210\}$, octahedron $o\{111\}$, diploid $s\{321\}$, diploid $\{421\}$, and trapezohedron $\{211\}$. The habit is nearly always either cubic, pyritohedral, or octahedral. Figures 387 to 394 represent typical crystals. The cube faces are commonly striated as in Fig. 407. The $\{hk0\}$ forms are so characteristic of pyrite that they are called pyritohedrons. Of these, the pyritohedron $\{210\}$ is the most common. Penetration twins of the pyritohedron

with the *a*-axis as the twinning axis are occasionally found. (See Fig. 257, page 127.)

H. = 6 to 6½. **Sp. gr.** 5.0 ± (5.027 if pure)

Color. Brass yellow. Luster, metallic. Streak, greenish to brownish-black.

Chemical Composition. Iron disulfid, FeS_2; (Fe = 46.6 per cent.). May contain copper, cobalt, nickel, arsenic, and gold; but of these only the cobalt and nickel are chemically combined.

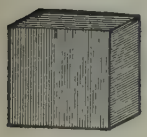


Fig. 387.

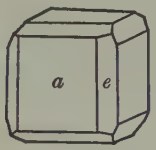


Fig. 388.

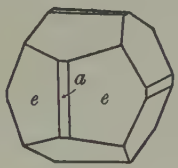


Fig. 389.

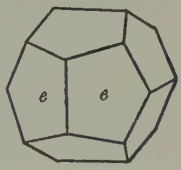


Fig. 390.

Fig. 391.

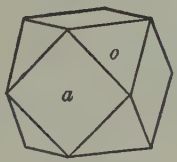


Fig. 392.

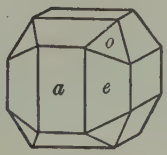


Fig. 393.

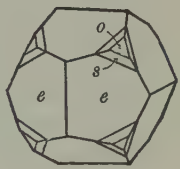


Fig. 394.

Figs. 387–394.—Pyrite crystals.

In the so-called cupriferous pyrite, the copper is in the form of chalcopyrite. The following are typical analyses:

	Fe	S	Cu	Misc.
French Creek, Penn.	44.2	54.1	0.05	
Arnsberg, Germany	46.4	51.4	1.0	Mn = 0.5; Co = 0.1; As = 0.6
Cornwall, Penn.	44.5	53.4	2.4	

Blowpipe Tests. Fusible at 3 to a magnetic globule. On charcoal it burns with a blue flame and gives off SO_2. In the

closed tube, pyrite gives a sublimate of sulfur and leaves a magnetic residue.

Soluble in cold HNO_3, but no sulfur separates unless the acid is heated.

Distinguishing Features. Pyrite is distinguished from pyrrhotite and chalcopyrite by superior hardness, and from marcasite, its dimorph, by crystal form and solubility in cold HNO_3.

Uses. Pyrite is used extensively in the manufacture of sulfuric acid, which is the basis of many chemical industries. Spain, Norway, Portugal, United States, and Italy are the principal producers. Pyrite is also an important low-grade copper ore at many localities. The copper is present as disseminated chalcopyrite. Pyrite is also often gold-bearing.

Occurrence. 1. As a vein mineral associated with other sulfids.

2. As a secondary mineral in igneous rocks, especially in the country rock around ore deposits.

3. As a dissemination in sedimentary rocks, such as shales and limestones, often replacing organisms.

4. As bedded deposits in metamorphic rocks, perhaps formed from original pyrrhotite.

5. As a contact-metamorphic mineral often associated with hematite and magnetite.

Smaltite, $(Co,Ni)As_2$

Form. Smaltite is usually massive without any cleavage, but occasionally is found in cubic crystals.

H. = $5\frac{1}{2}$. **Sp. gr.** 6.2±.

Color. Tin white to steel gray. Luster metallic.

Chemical Composition. Cobalt and nickel arsenid, $(Co,Ni)As_2$, varying from $CoAs_2$ (Co = 28.1 per cent.) to $NiAs_2$ (Ni = 28.1 per cent.). If the latter predominates, the mineral is called chloanthite. Iron and sulfur are usually present in small amounts. The following analyses illustrate the range in composition

	Co	Ni	Fe	As	S	Misc.
Atacama, Chili	24.1	1.2	4.1	70.8	0.1	Cu = 0.4
Wittichen, Germany	10.1	8.5	5.1	69.7	4.7	Cu = 0.9; Bi = 1.0
Schneeberg, Saxony	4.2	24.9	0.7	68.4	1.1	Bi = 0.2

Blowpipe Tests. On charcoal gives off arsin and fuses at 2½ to a magnetic globule, which colors the borax bead blue. In the closed tube it gives an arsenic mirror if strongly heated. In the open tube it gives minute octahedral crystals of As_2O_3.

Soluble in HNO_3 to a rose-red solution.

Distinguishing Features. Smaltite resembles arsenopyrite and can only safely be distinguished by blowpipe or chemical tests.

Uses. Smaltite is the chief ore of cobalt which is used principally as a blue pigment (a cobalt silicate called smalt.) Cobalt, Ontario, is the principal producer.

Occurrence. 1. As a vein mineral usually with silver or bismuth and in a gangue of calcite. Smaltite is often coated with erythrite, a hydrous cobalt arsenate known as "cobalt bloom."

MARCASITE GROUP—ORTHORHOMBIC

The following minerals: marcasite, FeS_2; arsenopyrite, FeAsS; löllingite, $FeAs_2$; glaucodot (Co,Fe)AsS; safflorite, $CoAs_2$; and rammelsbergite, $NiAs_2$, constitute an isomorphous group parallel to the pyrite group. They are orthorhombic in crystallization, have a hardness of 5 to 6½, and are tin-white to brass-yellow in color. Only the first two of these minerals are considered, as the others are rare.

Marcasite, FeS_2

Form. Marcasite occurs in orthorhombic crystals, in crystalline aggregates, and in rounded concretionary masses. Crystals are usually tabular in habit and often elongated in the direction

of the a-axis. Figures 395 to 397 represent typical crystals with the forms: $c\{001\}$, $m\{110\}$, $v\{013\}$. $mm(110:1\bar{1}0) = 74° 55'$. Twins with $m\{110\}$ as twin-plane are common.

H. = 6 to $6\frac{1}{2}$. **Sp. gr.** $4.9\pm$.

Color. Pale brass yellow with a greenish tinge. Almost tin-white when cleaned with dilute HCl (distinction from pyrite which is yellow). Luster metallic.

Chemical Composition. Iron disulfid, FeS_2; (Fe = 46.6 per cent.). Analyses often show small amounts of arsenic.

Blowpipe Tests. The same as for pyrite, except that it is decomposed by cold nitric acid with the separation of sulfur.

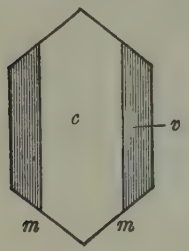


Fig. 395.

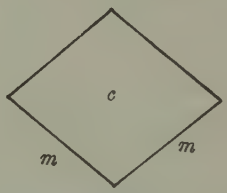


Fig. 396.

Fig. 397

Figs. 395–397.—Marcasite crystals.

Distinguishing Features. Marcasite is distinguished from pyrite by crystal form and by difference in color and behavior with nitric acid.

Uses. If found in sufficient quantity, marcasite could be used in the manufacture of sulfuric acid.

Occurrence. 1. In sedimentary rocks or associated with coal beds, often in concretions. Dover, England.

2. As a vein mineral formed near the surface at a low temperature and probably from acid solutions. Joplin district, Missouri.

ARSENOPYRITE, FeAsS

Form. Arsenopyrite is found in well-formed crystals, as well as in disseminated grains and compact masses. The crystals

are orthorhombic, similar in habit and angles to marcasite. Figures 398 and 399 represent typical crystals with the forms $m\{110\}$, $c\{001\}$, and $u\{014\}$.

H. = 5½ to 6. **Sp. gr.** 6.0±.

Color. Tin-white to light steel-gray. Luster, metallic.

Chemical Composition. Iron arsenid-sulfid, FeAsS; (Fe = 34.3, As = 46.0, S = 19.7). It often contains cobalt and grades into glaucodot.

Blowpipe Tests. On charcoal fuses (at 2) to a magnetic globule and gives off arsin. In the closed tube on gentle heating gives a red sublimate (AsS), but on further heating an arsenic mirror is formed. In the open tube minute crystals of As_2O_3 are deposited and SO_2 also formed.

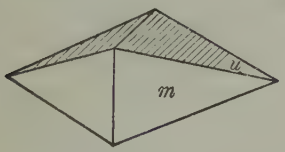


FIG. 398.

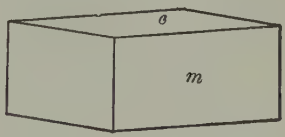


FIG. 399.

FIGS. 398, 399.—Arsenopyrite crystals.

Soluble in HNO_3 with the separation of S.

Distinguishing Features. Crystals of arsenopyrite resemble marcasite but are distinguished by color of fresh surface. Massive arsenopyrite resembles smaltite and often can only be distinguished by blowpipe tests.

Uses. Arsenopyrite is the chief source of the white arsenic (As_2O_3) of commerce. At Deloro, Canada, arsenopyrite is a gold ore.

Occurrence. 1. As an intermediate-temperature vein mineral associated with pyrite, chalcopyrite, galena, and other sulfids. Mother Lode of California.

2. In high-temperature veins.

3. In granite-pegmatites.

Calaverite, $AuTe_2$

Form. Calaverite usually occurs in small, striated, elongated crystals along seams. The crystals are complex monoclinic; some of the faces have such very high indices that the law of rational indices has been questioned.

Fracture, subconchoidal. No cleavage.

H. = $2\frac{1}{2}$. **Sp. gr.** 9.0±.

Color. Pale brass yellow, somewhat resembling pyrite. Metallic luster.

Chemical Composition. Gold tellurid, $AuTe_2$; (Au = 44 per cent.). It always contains some silver, usually from 2 to 4 per cent.

Blowpipe Tests. Easily fusible (at 1) on charcoal to a yellow button of gold, giving dense white fumes and coloring the flame bluish-green. The powdered numeral dropped into hot concentrated H_2SO_4 gives a purplish-red coloration.

Soluble in aqua regia with the separation of a little AgCl.

Distinguishing Features. Calaverite is distinguished from pyrite by its inferior hardness and elongated crystals.

Uses. An important ore of gold. At Cripple Creek, Colorado it is the chief source of gold. It also occurs in West Australia associated with sylvanite ($AuAgTe_4$). The name is derived from Calaveras county, California, where it was first found in the Stanislaus Mine.

Occurrence. 1. As a vein mineral. At Cripple Creek, fluorite is a common associate.

3. SULFO-SALTS

CHALCOPYRITE,	$CuFeS_2$
BORNITE,	Cu_5FeS_4
Jamesonte	$Pb_4FeSb_6S_{14}$
Pyrargyrite,	Ag_3SbS_3
TETRAHEDRITE,	$Cu_3SbS_3 + x(Fe, Zn)_6Sb_2S_9$
Stephanite,	Ag_5SbS_4
Polybasite,	$(Ag,Cu)_{16}Sb_2S_{11}$
Enargite,	Cu_3AsS_4

Under the sulfo-salts are included certain compounds of sulfur, salts of hypothetical acids which may be derived from ordinary oxygen acids by replacing S for O, as these two elements are similar chemically.

Three classes of these compounds may be distinguished: (1) Sulfoferrites, derivatives of H_3FeS_3 analogous to ferrous acid, H_3FeO_3; (2) Sulfarsenites and sulfantimonites, derivatives of H_3AsS_3 and H_3SbS_3 analogous to arsenious acid, H_3AsO_3 and antimonous acid, H_3SbO_3; (3) Sulfarsenates and sulfantimonates, derivatives of H_3AsS_4 and H_3SbS_4, analogous to arsenic acid, H_3AsO_4, and antimonic acid, H_3SbO_4.

There are also condensed acids derived from the above mentioned acids by the subtraction or addition of H_2S, just as condensed acids may be derived from oxygen acids by the subtraction or addition of H_2O. Thus chalcopyrite, $CuFeS_2$, is a salt of $HFeS_2$ derived from H_3FeS_3 ($H_3FeS_3 - H_2S = HFeS_2$). Jamesonite is a salt of $H_5Sb_3S_7$ ($3H_3SbS_3 - 2H_2S$). Stephanite is a salt of H_5SbS_4 ($H_3SbS_3 + H_2S$). Polybasite is a salt of $H_{16}Sb_2S_{11}$ ($2H_3SbS_3 + 5H_2S$).

The sulfo-salts are sometimes considered as double sulfids. Thus pyrargyrite Ag_3SbS_3 is written $3Ag_2S \cdot Sb_2S_3$.

About sixty sulfo-salt minerals are known, but most of them are rare.

CHALCOPYRITE, $CuFeS_2$

Form. Chalcopyrite occurs in crystals, in masses, and disseminated through the rock. The crystals belong to the tetragonal system, scalenohedral class, but are pseudotetrahedral and pseudo-octahedral in form. Fig. 400 represents a common type of crystal with the forms $p\{111\}$ and $z\{201\}$. This is a tetragonal bisphenoid and is distinguished from a tetrahedron by the striations.

H. = 3½ to 4. **Sp. gr.** 4.2±.

Color. Brass yellow, often with an iridescent tarnish, hence the name "peacock copper." Metallic luster.

Chemical Composition. Cuprous sulfoferrite, $CuFeS_2$; (Cu = 34.5 per cent.). Variations from this formula are usually due to admixed pyrite.

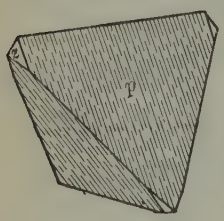


FIG. 400.—Chalcopyrite crystal.

Blowpipe Tests On charcoal fusible (at 2) to a magnetic globule which heated with sodium carbonate gives a copper button. In the closed tube it decrepitates and gives a sublimate of sulfur.

Soluble in HNO_3 to a green solution with the separation of sulfur from which NH_4OH gives a red-brown precipitate and blue solution.

Distinguishing Features. Chalcopyrite is distinguished from pyrite by difference in color and inferior hardness, and from gold by its brittleness.

Uses. Chalcopyrite is one of the principal ores of copper and the most widely distributed copper mineral.

Occurrence. 1. As a vein mineral associated with pyrite, galena, sphalerite, tetrahedrite, bornite, etc.

2. In basic igneous rocks with pyrrhotite, as a late magmatic mineral. Sudbury, Canada.

4. In fahlbands of schists and gneisses.

5. As a contact mineral with magnetite and hematite.

BORNITE, Cu_5FeS_4

Form. Bornite occurs in masses and disseminated specks, very rarely in rough cubic crystals.

H. = 3. **Sp. gr.** 5.1±.

Color. A red-brownish bronze with purple tarnish. Metallic luster. Slightly sectile.

Chemical Composition. Copper sulfoferrite, Cu_5FeS_4; (Cu = 63.3 per cent.). Analyses vary widely due to intermixture with chalcopyrite and chalcocite.

Blowpipe Tests. Fusible (at 2½) on charcoal R.F. to a magnetic globule. In the closed tube gives a faint sublimate of sulfur.

Soluble in HNO_3 to a green solution with the separation of S from which NH_4OH gives a red-brown precipitate and a blue solution.

Distinguishing Features. The peculiar color of bornite and its purple tarnish distinguishes it from all other minerals.

Uses. Bornite is an important ore of copper. It is usually intimately associated with chalcopyrite or chalcocite. Butte, Montana.

Occurrence. 1. As a vein mineral associated with chalcocite, chalcopyrite, and pyrite. Butte, Montana.

2. As a late magmatic mineral associated with chalcopyrite. Engels mine, Plumas county, California.

3. As a contact-metamorphic mineral between limestones and igneous rocks.

Jamesonite, $Pb_4FeSb_6S_{14}$

Form. Jamesonite occurs in delicate capillary crystals and in columnar and compact masses.

Cleavage. If cleavage is distinct, it is transverse to the length of the crystals.

H. = 2½. **Sp. gr.** 5.7±.

Color. Lead-gray. Metallic luster.

Chemical Composition. Lead and iron sulfantimonite, $Pb_4FeSb_6S_{14}$ (Pb = 40.3 per cent.).

Blowpipe Tests. On charcoal easily fusible (at 1) giving white and yellow coatings. In the closed tube gives a yellow sublimate of sulfur and a dark-red sublimate of Sb_2S_2O. With sodium carbonate on charcoal it gives a lead button.

Soluble in HCl with the evolution of H_2S. On cooling the solution needle crystals of $PbCl_2$ separate. Decomposed by HNO_3 with the separation of a white residue ($HSbO_3$).

Distinguishing Features. Jamesonite resembles stibnite, but has no distinct cleavage parallel to the length of the crystals.

Occurrence. 1. As a vein mineral. Sevier county, Arkansas.

Pyrargyrite, Ag_3SbS_3

Form. Pyrargyrite often occurs in small well-defined crystals belonging to the ditrigonal pyramidal class. The habit is usually prismatic, and the hexagonal prism, $\{11\bar{2}0\}$, the dominant form. Opposite ends of the crystal are differently terminated. Figure 401 represents a typical crystal; the striations indicate the hemimorphic character.

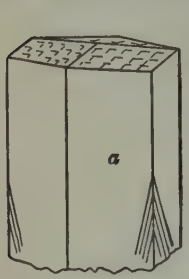


FIG. 401.—Pyrargyrite crystal.

H. = 2½. **Sp. gr.** 5.8±.

Color. Dark red to black. Translucent red on thin edges. Streak purple-red. Luster metallic-adamantine.

Optical Properties. $n_\gamma(3.08) - n_a(2.88) = 0.20$. Fragments are irregular and red in color, with high order interference colors.

Chemical Composition. Silver sulfantimonite, Ag_3SbS_3; (Ag = 59.9 per cent.). Arsenic replaces antimony to some extent. The corresponding sulfarsenite is called proustite. Together they constitute the ruby silver group.

Blowpipe Tests. On charcoal fuses easily (at 1) to a globule of silver sulfid giving a white sublimate. This globule with sodium

carbonate in R.F. gives a silver button. Heated intensely in the closed tube, it gives a slight red sublimate.

Decomposed by HNO_3 with the separation of sulfur and a white residue.

Distinguishing Features. Pyrargyrite is distinguished from other silver minerals (except proustite, Ag_3AsS_3) by the red fragments and streak, and from cuprite and cinnabar by blowpipe tests.

Uses. A valuable ore of silver, often associated with argentite, stephanite, and polybasite.

Occurrence. 1. As a vein mineral often formed at a late stage by ascending solutions. Tonopah, Nevada.

TETRAHEDRITE, $Cu_3SbS_3 + x(Fe,Zn)_6Sb_2S_9$

Form. Tetrahedrite occurs in masses, and also in crystals belonging to the hextetrahedral class of the isometric system.

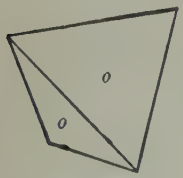


Fig. 402.

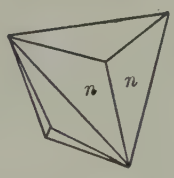


Fig. 403.

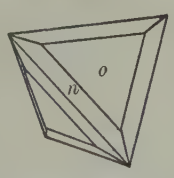


Fig. 404.

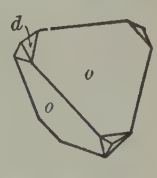


Fig. 405.

Figs. 402–405.—Tetrahedrite crystals.

The common forms are the tetrahedron $o\{111\}$, the tristetrahedron $n\{211\}$, and the dodecahedron $d\{110\}$. Figures 402 to 405 represent typical crystals.

H. = $3\frac{1}{2}$. **Sp. gr.** 4.7±.

Color. Dark iron-gray. Metallic luster. Brittle.

Chemical Composition. Copper sulfantimonite, $Cu_3SbS_3 + x(Fe,Zn)_6Sb_2S_9$, where $x = \frac{1}{10}$ to $\frac{1}{5}$. The copper is often replaced by silver and the antimony by arsenic. It grades into tennantite, the corresponding sulfarsenite. The following analyses illustrate the wide variation in chemical composition.

	Cu	Sb	S	As	Fe	Zn	Ag	Misc.
Fresney d'Oisans.....	45.4	28.8	24.5	tr	1.3	...	....	Pb = 0.1
Kapnik, Hungary.....	38.0	23.9	25.8	2.9	0.8	7.3	0.6	
Machetillo, Chili.....	36.7	20.7	25.3	6.5	1.2	6.9	2.9	
Cabarrus Co., N. C.....	30.7	17.8	25.5	11.5	1.4	2.5	10.5	
Poracs, Hungary.....	32.8	30.2	24.9	....	5.9	...	0.1	Hg = 5.6

Blowpipe Tests. Easily fusible (at 1½) giving dense white fumes and a white sublimate near the assay. The residue heated with sodium carbonate in R.F. gives metallic copper. In the closed tube it gives a dark red sublimate (Sb_2Sb_2O).

Soluble in HNO_3 to a green solution with the separation of sulfur and a white residue, $HSbO_3$.

Distinguishing Features. Tetrahedrite is apt to be confused with chalcocite. It is very brittle, while chalcocite is somewhat sectile.

Uses. Tetrahedrite is an ore of copper and silver known to miners as "gray copper." Highly argentiferous tetrahedrite is called freibergite.

Occurrence. 1. As a vein mineral often associated with chalcopyrite, galena, sphalerite, and siderite. Cornwall, England, and Oruro, Bolivia, are prominent localities.

2. In fahlbands of schists. *Fahlore* is a synonym of tetrahedrite.

Stephanite, Ag_5SbS_4

Form. Stephanite occurs disseminated, compact massive, more rarely in crystals. The crystals are orthorhombic, but pseudohexagonal and short prismatic in habit.

H. = 2½. **Sp. gr.** 6.2±.

Color. Dark gray to black. Very brittle. Metallic luster.

Chemical Composition. Silver sulfantimonite, Ag_5SbS_4; (Ag = 68.5 per cent.).

Blowpipe Tests. On charcoal easily fusible (at 1) to a globule giving dense fumes and a white sublimate of Sb_2O_3. The globule heated with sodium carbonate R.F. gives a silver button.

Decomposed by HNO_3 with the separation of sulfur and a white residue.

Distinguishing Features. Stephanite resembles argentite and tetrahedrite. Argentite is sectile, and tetrahedrite harder than stephanite.

Uses. A valuable ore of silver. It was a prominent mineral in the Comstock Lode of Nevada. Stephanite is known to miners as "brittle silver."

Occurrence. 1. As a vein mineral formed at a late stage by ascending solutions.

Polybasite, $(Ag,Cu)_{16}Sb_2S_{11}$

Form. Polybasite usually occurs in monoclinic pseudo-hexagonal crystals of tabular habit with triangular striations on the basal pinacoid.

H. = $2\frac{1}{2}$. **Sp. gr.** $6.1\pm$.

Color. Iron black. Metallic luster.

Optical Properties. $n > 1.93$. Very thin fragments are deep red translucent.

Chemical Composition. Silver and copper sulfantimonite $(Ag,Cu)_{16}Sb_2S_{11}$; (Ag = about 70 per cent.). Polybasite usually contains arsenic and thus grades into pearceite, $(Ag,Cu)_{16}As_2S_{11}$.

Blowpipe Tests. On charcoal fuses easily (at 1) to a globule and gives a white sublimate. The globule heated with sodium carbonate gives a metallic button. In order to get pure silver it is necessary to cupel the button.

Decomposed by HNO_3 with the separation of sulfur and a white residue ($HSbO_3$).

Distinguishing Features. The tabular crystals with triangular markings are distinctive.

Uses. Polybasite is an ore of silver. It occurs at Tonopah, Nevada, and at several mines in Colorado.

Occurrence. 1. As a vein mineral, formed at a late stage by ascending solutions. Aspen, Colorado.

Enargite, Cu_3AsS_4

Form. Enargite occurs in columnar masses and occasionally in prismatic orthorhombic crystals.

Cleavage. Prominent (in two directions at angles of 82° to each other).

H. = 3. **Sp. gr.** 4.4±.

Color. Dark gray to black.

Chemical Composition. Copper sulfarsenate, Cu_3AsS_4; (Cu = 48.3 per cent.). It usually contains a little antimony and a little iron. The corresponding sulfantimonate is a rare mineral known as famatinite.

Blowpipe Tests. Easily fusible at 1; sulfur dioxid masks the odor of arsin. In the closed tube gives a sublimate of sulfur. In the open tube it deposits minute octahedral crystals of As_2O_3 with adamantine luster and SO_2 gas is formed.

Soluble in HNO_3.

Distinguishing Features. The columnar structure and good cleavage are distinctive. It is distinguished from stibnite by its darker color.

Uses. Enargite is an ore of copper, occurring at Butte, Montana, and at many localities in South America. Near Butte white arsenic (As_2O_3) is recovered from smelter smoke.

Occurrence. 1. In veins and replacement deposits formed at intermediate depths and temperatures. At Tintic, Utah, enargite is the original source of several copper arsenate minerals.

4. HALOIDS

The haloids comprise chlorids, bromids, iodids, and fluorids which are salts of HCl, HBr, HI, and HF respectively. Comparatively few haloids occur in nature, but several of them are very common minerals. All the minerals are normal anhydrous salts with the exception of carnallite.

A. Normal anhydrous haloids

HALITE, NaCl
Sylvite, KCl
Cerargyrite, AgCl
FLUORITE, CaF_2
Cryolite, Na_3AlF_6

B. Basic and hydrous haloids

Carnallite, $KMgCl_3 \cdot 6H_2O$

HALITE, NaCl

Form. Halite occurs in crystals, and in cleavable, granular, and fibrous masses. Crystals are isometric, usually cubes (Fig. 406), sometimes hopper-shaped (Fig. 407), rarely in octahedrons or cubo-octahedrons (Fig. 408).

Cleavage. The perfect cubic cleavage is a marked feature of halite. A dodecahedral {110} parting is developed by pressure applied on the cube-edges by a hammer or in a vise (Fig. 265, page 131).

H. = 2½. **Sp. gr.** 2.1±.

Color. Colorless and white, often reddish or gray, and sometimes deep blue in patches.

Optical Properties. Isotropic. $n = 1.54$. Recrystallizes from a water solution in squares, often hopper-shaped (Fig. 490), which are dark between crossed nicols and have low relief in clove oil.

Chemical Composition. Sodium chlorid, NaCl; (Na = 39.4 per cent.). Halite may contain $MgCl_2$,$MgSO_4$,$CaCl_2$, and $CaSO_4$. It is to these impurities that the deliquescence of table salt is due.

Blowpipe Tests. Fuses easily (at 1), giving an intense yellow flame. With CuO in $NaPO_3$ bead it gives an azure-blue flame.

Soluble in cold water.

Distinguishing Features. Distinguished from most minerals by its cubic cleavage. It has a pleasant saline taste and not the sharp taste of sylvite.

Uses. Halite is the chief source of sodium compounds used extensively in the manufacture of soap and glass, and also as

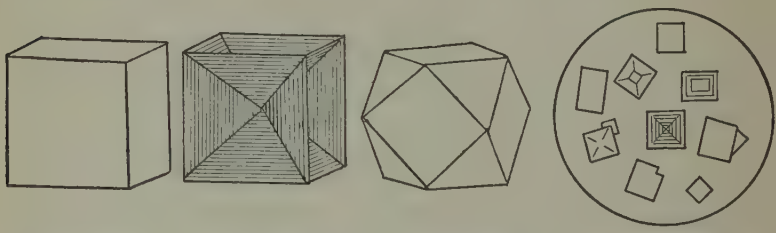


Fig. 406. Fig. 407. Fig. 408. Fig. 409.

Figs. 406–409.—Halite crystals.

table salt and as a preservative. Salt brines furnish bromin. Salt is obtained (1) directly by the mining of rock-salt as at Petite Anse, Louisiana, and Lyons, Kansas; (2) by pumping brine to surface and evaporating as at Syracuse, New York, and Hutchinson, Kansas; and (3) by solar evaporation as at Great Salt Lake, Utah.

Occurrence. 1. Occurs in beds associated with anhydrite gypsum, and occasionally with other chlorids and sulfates These deposits are formed by the evaporation of sea-water Important localities are Stassfurt, Germany; Wieliczka, Poland Cheshire, England; western New York; Saginaw, Michigan and central Kansas.

Sylvite, KCl

Form. Sylvite occurs in cleavable and granular masses and in well-formed cubic or cubo-octahedral (like Fig. 408) crystals. Etch-figures indicate that sylvite belongs to the gyroidal class of the isometric system.

Cleavage. Perfect cubic cleavage.

Color. Colorless or white, sometimes with bluish opalescence. Taste, sharp saline.

H. = 2. **Sp. gr.** 2.0±.

Optical Properties. Isotropic. $n = 1.49$ (clove oil). Recrystallizes from water solution in square crystals with a tendency toward skeleton crystals (Fig. 410). These are dark between crossed nicols and have moderate relief in clove oil.

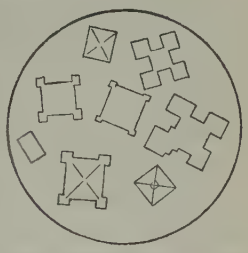


FIG. 410.—Sylvite recrystallized.

Chemical Composition. Potassium chlorid, KCl; (K = 52.4 per cent.). It may contain NaCl.

Blowpipe Tests. Fuses easily (at 1½), coloring the flame violet. With CuO in a $NaPO_3$ bead it gives an azure-blue flame.

Soluble in cold water.

Distinguishing Features. It is recognized by its cubic cleavage and its sharp saline taste.

Uses. Used as a fertilizer and a source of potassium salts.

Occurrence. 1. In salt beds with halite, anhydrite, kainite, and carnallite. It is sometimes a secondary mineral formed from carnallite ($KMgCl_3 \cdot 6H_2O$). Stassfurt, Germany, and Mulhouse, Alsace.

2. As a volcanic sublimate on lava. Vesuvius.

Cerargyrite, AgCl

Form. Cerargyrite usually occurs as a thin crust or seam, but small cubic crystals are also found.

H. = 2. **Sp. gr.** 5.5±.

Color. Gray, greenish, or violet. Luster, waxy to adamantine. Very sectile.

Optical Properties. Isotropic. $n = 2.06$. May be hammered to a thin sheet which is translucent, but dark between crossed nicols. A few drops of NH_4OH will give minute octahedral crystals (AgCl).

Chemical Composition. Silver chlorid, AgCl (Ag = 75.3 per cent.).

Blowpipe Tests. On charcoal fuses easily (at 1), giving a silver button. A fragment touched with a $NaPO_3$ bead saturated with CuO gives an intense azure-blue flame.

Insoluble in acids, but soluble in NH_4OH.

Distinguishing Features. Cerargyrite is easily overlooked but on close inspection its appearance and sectile character are distinctive.

Uses. An ore of silver in the western United States, Mexico and Chili. The miner's name for it is "horn silver."

Occurrence. 1. A mineral characteristic of the upper part of ore deposits. It is formed by the action of chlorid-bearing meteoric waters on other silver minerals, and therefore is prominent in arid regions. Poorman mine, Idaho.

FLUORITE, CaF_2

Form. Fluorite usually occurs in cleavable masses, but also often in distinct crystals. The crystallization is isometric (hexoctahedral class). Usual forms: $a\{100\}$, $f\{310\}$, $t\{421\}$, $d\{110\}$, $o\{111\}$. The habit is practically always cubic; the other forms are subordinate. Octahedral crystals are rare. At some localities apparent octahedra are built up of minute cubes in parallel position. Figures 411 to 414 represent typical crystals of fluorite. Figure 414 is a penetration twin with the cube diagonal as twin axis. Vicinal faces with high indices such as $\{32{\cdot}1{\cdot}0\}$ are often found on these crystals.

Cleavage. One of the most important characters of fluorite is the perfect octahedral cleavage. On a cube this will show a

triangular faces at the vertices, or at least as cracks in this direction, as shown in Fig. 411.

H. = 4. **Sp. gr.** 3.2± (3.18, if pure)

Color. Usually colorless or some tint or shade of violet or green, rarely yellow, brown, blue or pink. The color is probably due to hydrocarbons. Some crystals from Cumberland are green by transmitted light, but blue by reflected light. This property, also possessed by some aniline colors such as red-ink, is known as fluorescence, a name derived from the mineral fluorite. Some varieties of fluorite are also phosphorescent, that is, after being heated, continue to emit light in the dark.

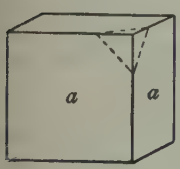


Fig. 411.

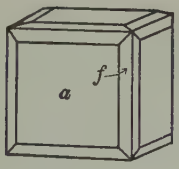


Fig. 412.

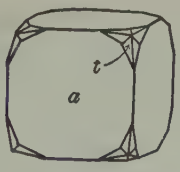


Fig. 413.

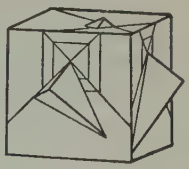


Fig. 414.

Optical Properties. Isotropic. n = 1.434, hence high relief in clove oil. Fragments are triangular, colorless, and dark between crossed nicols. (See Fig. 371, page 205.)

Chemical Composition. Calcium fluorid CaF_2; (F = 48.9 per cent.). Impurities are usually calcite, dolomite, barite or quartz. Free fluorin has been detected in some fluorite. Fluorite is the only common fluorid occurring in nature.

Blowpipe Tests. In the closed tube decrepitates. Fuses (at 3) to an enamel coloring the flame red.

Distinguishing Features. Fluorite is distinguished by the cubic crystals, octahedral cleavage, and specific gravity, which is a little higher than the average non-metallic mineral.

Soluble in H_2SO_4 with evolution of HF, which etches glass. Dilute H_2SO_4 added to a hydrochloric acid solution of the mineral gives a crystalline precipitate of hydrous calcium sulfate.

Uses. The main use of fluorite is a flux in iron smelting and

foundry work. Western Kentucky and southern Illinois are the principal sources of fluorite in this country. Minor uses are the manufacture of enamels, opalescent glass, and hydrofluoric acid. Moissan in his work on fluorin used vessels made of fluorite.

Occurrence. 1. As a vein mineral associated with galena, sphalerite, calcite, and barite. Typical localities are fissure veins in the limestone of western Kentucky and lead mines in the north of England, where magnificent museum specimens are found.

2. In tin-stone veins associated with cassiterite, apatite, topaz, and lepidolite. Zinnwald, Bohemia.

3. In limestones. St. Louis, Missouri.

Cryolite, $3NaF \cdot AlF_3$

Form. Massive and in pseudo-cubic (monoclinic) crystals often in parallel position.

Cleavage. Imperfect in three directions at nearly right angles.

H. = $2\frac{1}{2}$. **Sp. gr.** 3.0±.

Color. White, sometimes brown. Translucent.

Optical Properties. $n\beta = 1.36$. Low relief in water (for water, $n = 1.333$). Double refraction very weak. Fragments are roughly rectangular or irregular. Interference colors are first order gray.

Chemical Composition. Sodium aluminum fluorid, $3NaF \cdot AlF_3$ (Al = 12.8 per cent., Na = 32.8).

Blowpipe Tests. Easily fusible (at 1) giving an intense yellow flame.

Soluble in H_2SO_4 with the evolution of HF.

Distinguishing Features. The translucent white masses resemble fluorite but lack the good cleavage of the latter. Fragments placed in water look as though they had partially dissolved.

Uses. Formerly used as a source of aluminum, but now used as a bath in the electrolytic production of aluminum from bauxite. It is also used in the manufacture of sodium and aluminum salts at Natrona, Pa. The mineral is shipped from Greenland.

Occurrence. 1. In granite pegmatites. The most important

locality is Ivigtut, in southern Greenland, where an immense vein-like mass of cryolite containing siderite, sphalerite, galena, etc., occurs in a porphyritic granite. It also occurs at St. Peter's Dome in El Paso county, Colorado.

Carnallite, $KMgCl_3.6H_2O$

Form. Massive or granular. Crystals (orthorhombic) are very rare.

Cleavage. No cleavage, but has conchoidal fracture.

H. = 1. **Sp. gr.** 1.6±.

Color. Colorless or reddish. Luster, greasy. Very deliquescent.

Optical Properties. $n\gamma(1.49) - n\alpha(1.46) = 0.03$. Recrystallized from water solution, it forms in order (1) isotropic squares of KCl, (2) rectangular twinned crystals of $KMgCl_3 \cdot 6H_2O$, and (3) streaked aggregates of $MgCl_2$ (Fig. 415).

FIG. 415.

Chemical Composition. Hydrous potassium magnesium chlorid $KMgCl_3 \cdot 6H_2O$ or $KCl \cdot MgCl_2 \cdot 6H_2O$; (KCl = 26.8 per cent.) (H_2O = 39.0 per cent.).

Blowpipe Tests. Fusible at 1½, coloring the flame violet. With CuO in a $NaPO_3$ bead it gives an azure-blue flame. Gives abundant water in the closed tube.

Soluble in water.

Distinguishing Features. Carnallite is distinguished by its bitter taste and lack of cleavage.

Uses. Carnallite is used as a fertilizer and in the manufacture of potassium salts. KCl crystallizes out of a water solution of carnallite.

Occurrence. 1. In salt beds associated with anhydrite, halite, sylvite, and kainite. Stassfurt, Prussia, is the most prominent locality.

5. OXIDS

QUARTZ,	SiO_2
CHALCEDONY,	SiO_2
OPAL,	$SiO_2(H_2O)_x$
Tridymite	SiO_2
Cristobalite	SiO_2
Ice,	H_2O
Cuprite,	Cu_2O
CORUNDUM,	Al_2O_3
HEMATITE,	Fe_2O_3
Turyite,	$Fe_2O_3(H_2O)_x$
CASSITERITE,	SnO_2
Rutile,	TiO_2
Pyrolusite,	MnO_2
Stibiconite,	$Sb_2O_4(H_2O)_x$

Among the oxids are some of the most common and widely distributed minerals. The silica minerals are placed first, and after them the monoxids, R_2O and RO, the sesquioxids, R_2O_3, and the dioxids, RO_2 in the order named.

The minerals of the spinel group, sometimes considered as double oxids of the type $RO{\cdot}R_2O_3$, are placed in a separate division, the aluminates, etc.

QUARTZ, SiO_2

Form. Crystals of quartz are very common, both large and small, loose and attached. There are crystalline aggregates of various kinds as well as massive, granular, and compact varieties.

Quartz crystallizes in the trigonal trapezohedral class of the hexagonal system. $\dot{c} = 1.099$. Usual forms: $r\{10\bar{1}1\}$, $z\{01\bar{1}1\}$, $m\{10\bar{1}0\}$, $s\{11\bar{2}1\}$, $x\{51\bar{6}1\}$. Interfacial angles: $mr(10\bar{1}0:10\bar{1}1) = 38°\ 13'$; $rr(10\bar{1}1:\bar{1}101) = 85°\ 46'$; $rz(10\bar{1}1:\ 011\bar{1}) = 46°\ 16'$; $ms(10\bar{1}0:\ 11\bar{2}1) = 37°\ 58'$; $mz(10\bar{1}0\ :\ 01\bar{1}1) = 66°\ 52'$; $mx(10\bar{1}0\ 51\bar{6}1) = 12°\ 1'$; $mm(10\bar{1}0\ :\ 01\bar{1}0) = 60°\ 0'$. Figures 416–421

represent typical crystals. The habit varies from prismatic to pyramidal. The two rhombohedrons r and z are often in equal combination (Figs. 416 , 419) and apparently form a hexagonal bipyramid. The s face at alternate vertices proves the trigonal character. Figures 420 and 421 are more complex with $x_1\{6\bar{1}\bar{5}1\}$ and $s_1\{2\bar{1}\bar{1}1\}$.

Cleavage, practically absent (an imperfect cleavage parallel to r is occasionally noticed).

H. = 7. **Sp. gr.** 2.66±.

Color, more often white or colorless, but may be any color. Luster, vitreous. Transparent to translucent, rarely opaque.

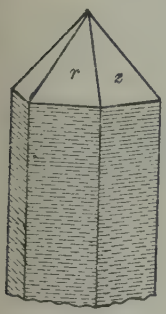


FIG. 416.

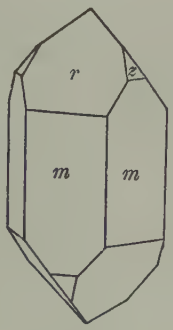


FIG. 418.

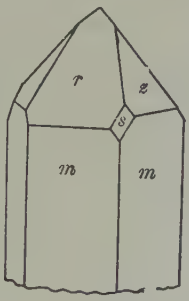


FIG. 418.

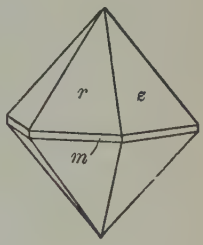


FIG. 419.

Optical Properties. $n_\gamma(1.553) - n_\alpha(1.544) = 0.009$. Double refraction rather weak. Fragments are irregular, with low relief in clove oil ($n >$ clove oil) and upper first-order interference colors.

In thick basal ($\perp$ to c-axis) sections quartz shows rotary polarization, *i.e.*, in monochromatic light a section only becomes dark by rotating one nicol. For red light the angle of rotation is 13° for each millimeter of thickness. Sections from crystals like Fig. 421 rotate the plane to the right, and those from crystals like Fig. 420 rotate the plane to the left.

Chemical Composition. Silica or silicon dioxid, SiO_2. Varia-

tions in analyses are due to inclusions such as chlorite, tourmaline, rutile, etc.

Blowpipe Tests. Infusible even on the thinnest edges. When fused with an equal volume of sodium carbonate, effervesces and gives a colorless glass ($Na_2CO_3 + SiO_2 = CO_2 + Na_2SiO_3$.) Insoluble in a $NaPO_3$ bead.

Insoluble in ordinary acids. Soluble in HF.

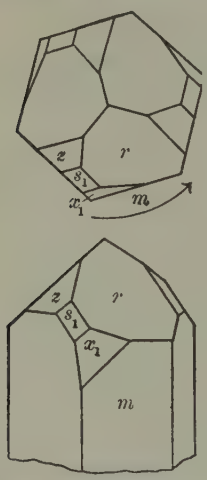


FIG. 420.—Left-handed quartz crystal.[1]

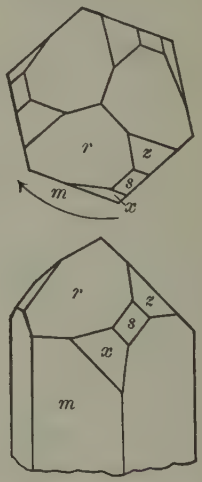


FIG. 421.—Right-handed quartz crystal.

Distinguishing Features. Quartz often resembles calcite but is distinguished by its superior hardness and lack of cleavage. From the other forms of silica it is distinguished by its indices of refraction.

Uses. Quartz in the form of rock crystal, amethyst, and smoky quartz is used for ornamental purposes, in the form of rock crystal for optical apparatus, in the form of sand for glass-making, and in the form of pulverized quartz for pottery and porcelain and as an abrasive.

[1] This figure is drawn as if the axis had been rotated to the right instead of to the left, as ordinarily. This brings out the enantimorphous relation to the right-handed crystal.

Occurrence. 1. As normal constituent of the acid igneous rocks (rhyolites and granites). (β-quartz.)

2. As an abnormal constituent of the basic igneous rocks, especially basalts (quartz basalts).

3. As a vein mineral, often the gangue of ores. Quartz is the most common vein mineral. (α-quartz).

4. As the chief constituent of sandstones and quartzites.

5. As a replacement mineral in various rocks, often occurring as pseudomorphs after various minerals, and as petrifactions.

6. As the chief constituent of river and beach sands.

CHALCEDONY, SiO_2

Form. Chalcedony occurs in compact masses and in cavities in colloform crusts. Although chalcedony is never found in distinct crystals, it is crystalline as the examination of thin sections or fragments in polarized light will show.

Fracture, more or less conchoidal. No cleavage.

H. = 7. **Sp. gr.** 2.6±.

Color, colorless, white, or any color, often banded and variegated. Red and brown varieties are called jasper, and the banded and variegated varieties, agate. Translucent to opaque. Luster, waxy to dull.

Optical Properties. $n_\gamma(1.543) - n_\alpha(1.532) = 0.011$. Double refraction rather low. Fragments are irregular with n slightly lower than clove oil. The aggregate structure with low order interference colors in spots and streaks is highly characteristic of chalcedony and usually distinguishes it from quartz.

Chemical Composition. Silica, SiO_2.

Blowpipe Tests. Same as for quartz except that it gives a small amount of water in the closed tube.

Distinguishing Features. Chalcedony is distinguished from most minerals of similar appearance by its greater hardness. From the other silica minerals it is distinguished by its dull luster. (Quartz has vitreous luster and opal, greasy luster.)

Uses. Agate, chrysoprase (apple-green, translucent chalcedony), and jasper are used as ornamental stones.

Occurrence. 1. As a secondary mineral in seams and cavities of various rocks, especially the volcanic igneous rocks.

2. As chert or flint and jasper occurring in concretions, lenses or layers in sedimentary rocks. The origin is doubtful. In the Joplin district the zinc ores occur in a brecciated chert, which covers large areas.

3. As a low-temperature vein mineral, often the gangue of gold, silver, and mercury ores.

OPAL, $SiO_2(H_2O)_x$

Form. Opal usually occurs in seams and cavities, but is also disseminated and massive. It is one of the typical amorphous minerals and so in cavities it often has a colloform structure.

Fracture, conchoidal. No cleavage.

H. = 5½ to 6½. **Sp. gr.** 2.1± (very light).

Color, white, colorless, or almost any color. Usually translucent. Luster, more or less greasy.

Optical Properties. Isotropic. $n = 1.45$. Fragments are irregular, usually dark between crossed nicols, and have high relief in clove oil (n less than clove oil, Becke test). Some varieties, notably hyalite, show weak double refraction, which is due to strain. Opal is often intimately mixed with chalcedony.

Chemical Composition. Hydrous silica $SiO_2 \cdot (H_2O)_x$ with water varying from 3 to 12 per cent. Like most amorphous minerals it is very apt to contain impurities. The following are typical analyses:

	SiO_2	H_2O	Al_2O_3	Fe_2O_3	CaO	MgO
Waltsch, Bohemia	95.5	3.0	...	0.8	0.2	
Washington Co., Ga.	91.9	5.8	1.4	...	...	0.9
Faroe Islands	88.7	8.0	1.0	..	0.5	1.5
Meronitz, Bohemia	83.7	11.5	...	3.6	1.6	0.7

Blowpipe Tests. Infusible, but becomes opaque. In the closed tube yields water.

Insoluble in the ordinary acids. Soluble in HF and also soluble in KOH.

Distinguishing Features. Opal may resemble chalcedony but has a lower specific gravity, is a little softer, and usually has a greasy luster.

Uses. The opal with play of colors known as precious opal and also the red or fire-opal are well known gems. The best precious opals are found in New South Wales and in Hungary, while the fire-opal is found principally in Mexico.

Occurrence. 1. As a characteristic mineral in cavities and along the seams of igneous rocks.

2. In volcanic tuffs as a replacement of wood (opalized wood or wood opal).

3. As siliceous sinter (geyserite) formed around hot springs and geysers. Yellowstone National Park is a prominent locality.

4. As the principal constituent of diatomaceous earth or diatomite. Diatoms and radiolaria secrete casts of opal silica.

Tridymite, SiO_2

Form. Tridymite usually occurs in the form of minute crystals. The habit is pseudohexagonal tabular; twinned crystals are common. The high-temperature β-tridymite is hexagonal but on cooling to the low-temperature α-tridymite (probably orthrombic) it retains the hexagonal form.

H. = 7. **Sp. gr.** = 2.27.

Color, colorless.

Optical Properties. $n_\gamma(1.473) - n_\alpha(1.469) = 0.004$. Fragments are six-sided plates or irregular with fair relief in clove oil. The double refraction is very weak.

Chemical Composition. Silica, SiO_2, the same as that of quartz.

Blowpipe Tests. Infusible before the blowpipe.

Insoluble in ordinary acids.

Distinguishing Features. Optical tests are necessary to distinguish tridymite from quartz and cristobalite. The indices of refraction of tridymite are less than 1.480, while those of cristobalite are greater than 1.480.

Occurrence. 1. In volcanic igneous rocks usually in cavities and probably produced by hot gases after the main period of rock formation. Obsidian Cliff, Yellowstone National Park.

Cristobalite, SiO_2

Form. Cristobalite occurs in spherical aggregates or in minute pseudo-octahedral crystals. The high-temperature β-cristobalite is isometric, but on changing to α-cristobalite it retains the isometric form. It is sometimes found in pseudomorphs after tridymite.

H. = 7. **Sp. gr.** = 2.33.

Color. White subtranslucent.

Optical Properties. $n_\gamma(1.487) - n_\alpha(1.484) = 0.003$. Fragments are irregular with fair relief in clove oil. The double refraction is very weak.

Chemical Composition. Silica, SiO_2, the same as that of tridymite and quartz.

Blowpipe Tests. Infusible before the blowpipe. On heating it becomes somewhat transparent and on cooling it suddenly becomes subtranslucent again. This change is due to the change of the high-temperature β-cristobalite to α-cristobalite. Insoluble in ordinary acids.

Distinguishing Features. The characteristic behavior before the blowpipe distinguishes it from similar minerals. In occurrence and general characters it is much like tridymite, but its indices of refraction are greater than 1.480 while those of tridymite are less than 1.480.

Occurrence. 1. In volcanic igneous rocks usually in cavities and probably formed by hot gases after the main period of rock formation. Tehama County, California.

Stability Relations of the Silica Minerals

Silica exists in at least seven well-defined polymorphous forms, each of which is stable between certain temperature limits as shown in Fig. 422. Ordinary vein quartz is stable up to 575°C.

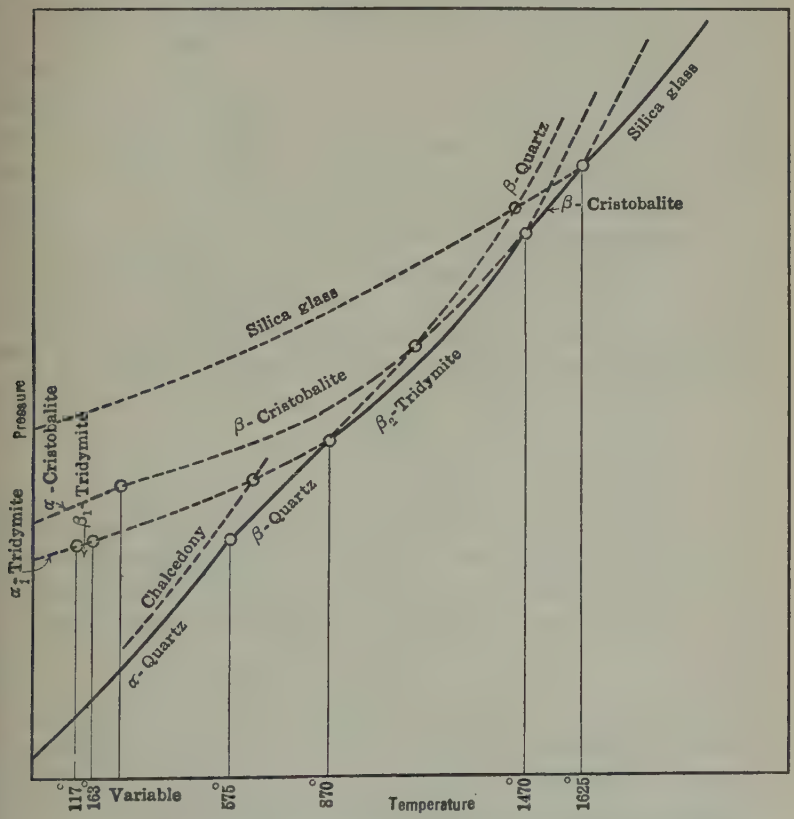


FIG. 422.—Stability diagram of the silica minerals. (After Fenner.)

At that temperature there is a sudden change in the indices of refraction and some of the other properties, and it passes into the form known as β-quartz. This form is the one char-

acteristic of igneous rocks, especially rhyolite porphyry and granite porphyry. No specimens of β-quartz exist at ordinary temperature for it has changed to α-quartz. At 870°C. β-quartz changes suddenly to β_2-tridymite, and at 1470°C. this changes to β-cristobalite. At 1625°C. cristobalite melts to silica glass. On cooling, β-cristobalite changes at temperatures ranging from 220° to 275°C. to another form called α-cristobalite.

Similarly β_2-tridymite changes to β_1-tridymite at 163°C. and this again to α-tridymite at 117°C. The cristobalite and tridymite in mineral collections are each the α-forms but usually retain the crystal habit of the β-forms. The relation of chalcedony to the other forms of silica is uncertain and opal can not be treated at all from the standpoint of the phase rule. It is a two-phase system, for it consists of solution of water in amorphous silica and is of colloidal origin. The diagram of Fig. 422 has been worked out in the Geophysical Laboratory of the Carnegie Institution of Washington.

Ice, H_2O

Form. Ice, the solid form of H_2O, occurs in frost and snow crystals and in massive and granular forms. Ice (and snow) crystallizes in the dihexagonal pyramidal class of the hexagonal system. Snow crystals are skeleton crystals of great variety. The frontispiece shows a number of microphotographs of snow crystals.

H. = 1½. **Sp. gr.** = 0.9167.

Color. Colorless to white, bluish in thick layers. Luster, vitreous.

Optical Properties. $n_\gamma(1.313) = n_\alpha(1.309) = 0.004$. Optically positive.

Occurrence. 1. In the form of snow, frost, and hail.
2. On the surface of rivers, ponds, and lakes.
3. In the polar regions.
4. In glaciers.

Cuprite, Cu_2O

Form. Cuprite is found in crystals, in crystalline aggregates, and in fine-grained masses. Crystals are isometric; the common forms are the cube (*a*), octahedron (*o*), and dodecahedron (*d*). The habit is usually determined by one of these forms. (Figs. 423–426.) Capillary cuprite found in Arizona proves to be elongate cubes.

H. = 3½ to 4. **Sp. gr.** 6.0±.

Color. Dark red to brownish-red. Translucent to opaque. Streak, brownish-red. Luster, metallic-adamantine. Imperfect cleavage.

Optical Properties. Isotropic. $n = 2.85$. Fragments are irregular, translucent red, and dark between crossed nicols.

Fig. 423.

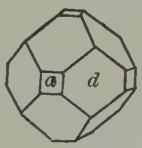


Fig. 424.

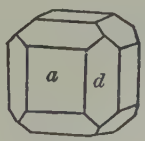


Fig. 425.

Fig. 426.

Chemical Composition. Cuprous oxid, Cu_2O; (Cu = 88.8 per cent.). Iron oxid is the most frequent impurity.

Blowpipe Tests. On charcoal fuses (at 2½) to a copper button.

Soluble in HNO_3 to a green solution.

Distinguishing Features. Cuprite is recognized by the isometric crystals, adamantine luster, and absence of perfect cleavage.

Uses. Cuprite is a valuable copper ore on account of the high percentage of copper. Bisbee, Arizona, is an important locality.

Occurrence. 1. In the oxidized zone of ore deposits associated with other copper minerals, especially native copper. Bisbee, Arizona.

HEMATITE GROUP—HEXAGONAL

Corundum and hematite form a perfect isomorphous group, although intermediate compounds are lacking. With them is sometimes placed ilmenite, but it is more properly considered a ferrous metatitanite, $FeTiO_3$. It belongs to a different crystal class, the trigonal rhombohedral class.

CORUNDUM, Al_2O_3

Form. Corundum is found in rough, loose crystals, in cleavable masses and disseminated through rock in small crystals or grains. The crystals belong to the scalenohedral class of the

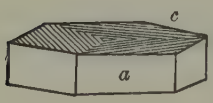


Fig. 427.

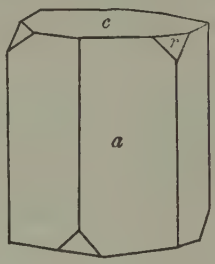


Fig. 428.

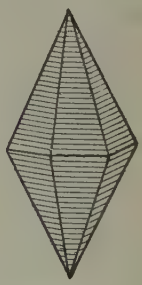


Fig. 429.

hexagonal system. Usual forms: $c\{0001\}$, $r\{10\bar{1}1\}$, $a\{11\bar{2}0\}$, $n\{22\bar{4}3\}$. Interfacial angles: $cr(0001:10\bar{1}1) = 57°\ 34'$, $rr(10\bar{1}1:\bar{1}101) = 93°\ 56'$, $cn(0001:22\bar{4}3) = 61°\ 11'$; $nn(22\bar{4}3:4\bar{2}\bar{2}3) = 51°\ 58'$. Habit prismatic (Fig. 428), tabular (Fig. 427), and steep pyramidal (Fig. 429). The trigonal character is shown by the r faces at alternate vertices and by the triangular striations on the basal pinacoid c.

Cleavage. There is often parting parallel to c and r. The rhombohedral parting greatly resembles cubic cleavage ($rr = 93°\ 56'$).

H. = 9. **Sp. gr.** 4.0±.

Color. Bluish-gray is the most common color, but brown, red, pink, green, bright blue, and white colors are not at all rare. Usually translucent. Luster, sub-adamantine.

Optical Properties. $n_\gamma(1.767) - n_\alpha(1.759) = 0.008$. Double refraction rather low. Fragments are irregular with first-order interference colors and index of refraction greater than methylene iodid. Large deep-colored fragments or small crystals are pleochroic.

Chemical Composition. Alumina or aluminum oxid, Al_2O_3; (Al = 52.9 per cent.). Emery is a dark-colored mixture of corundum with magnetite, hematite or spinel.

Blowpipe Tests. Infusible. When intensely heated with $Co(NO_3)_2$ solution it becomes deep blue.

Insoluble in acids. Decomposed by fusion with $KHSO_4$.

Distinguishing Features. Corundum is recognized by its extreme hardness (it is often altered on the exterior to soft micaceous product), by its cleavage, and by its high specific gravity.

Uses. Certain varieties of corundum are valuable gems. Ruby, the transparent red corundum, is even more valuable than diamond. Sapphire is the blue transparent corundum. Colorless stones are known as white sapphires. The best rubies come from Burma, and the best sapphires from Ceylon.

Artificial rubies and sapphires are now produced synthetically in Paris. They are with difficulty distinguished from natural stones.

Corundum is also used as an abrasive, either as the pure cleavable mineral or as the mixture known as emery. Corundum is mined in Ontario, Canada, and emery in Asiatic Turkey.

Artificial corundum is now made by heating bauxite in the electric furnace. It is sold under the trade names alundum and aloxite.

Occurrence. 1. In certain igneous rocks such as syenites and nepheline syenites in which an excess of Al_2O_3 has crystallized out as corundum, just as an excess of SiO_2 crystallizes as quartz in granites. Craigmont, Ontario.

2. In peridotites along the borders of adjacent rocks. In North Carolina the country rocks are gneisses, but the mode of origin is doubtful.

3. In crystalline limestones (Burma, New York, New Jersey).

4. In lamprophyre dikes, probably the result of absorption of shale and subsequent recrystallization of the excess of alumina. Yogo Gulch, Montana. Emery is associated with limestone at Naxos, Greece, and perhaps is the metamorphic equivalent of bauxite.

5. In sands and gravels. The gem-bearing gravels of Ceylon furnish sapphire and other varieties of corundum.

HEMATITE, Fe_2O_3

Form. Hematite is found in a variety of forms: small crystals in cavities, micaceous, fibrous, oölitic, and massive compact.

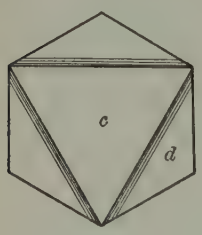


Fig. 430.

Fig. 431.

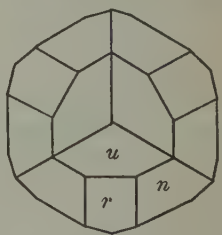


Fig. 432.

Figs. 430–432.—Hematite crystals.

Some of the red massive minerals called hematite are probably turyite, its amorphous equivalent.

Crystals are hexagonal, usually tabular or low rhombohedral in habit (Figs. 430, 431). The island of Elba furnishes good crystals with the forms $u\{10\bar{1}4\}$, $r\{10\bar{1}1\}$, and $n\{22\bar{4}3\}$ represented in plan by Fig. 432. $cr(0001:10\bar{1}1) = 57° 37.$

H. = 6. **Sp. gr.** 5.2±.

Color. Iron-black to dark red. Streak, brownish-red. **Luster,** metallic to dull. Opaque, but translucent red in very

thin scales. These scales are dark between crossed nicols (basal sections).

Chemical Composition. Ferric oxid, Fe_2O_3; (Fe = 70.0 per cent.). The iron is sometimes partly replaced by titanium and magnesium.

Blowpipe Tests. Fusible with difficulty (5½). On charcoal in R.F. becomes magnetic. Gives bead tests for iron.

Slowly soluble in concentrated HCl.

Distinguishing Features. Hematite is distinguished from magnetite, ilmenite, and limonite by its brownish-red streak and from turyite by its crystalline nature, greater hardness, and absence of water.

Uses. Hematite is the principal ore of iron; the Lake Superior district furnishes the principal domestic supply.

Occurrence. 1. In basic igneous rocks as a late magmatic mineral. Engels Mine, Plumas county, California.

2. In cavities of lavas as a volcanic sublimate. Vesuvius.

3. In contact-metamorphic deposits often associated with magnetite and pyrite.

4. As a metasomatic replacement of cherty iron carbonate. This origin is assigned to the Lake Superior hematite.

5. In metamorphic rocks often forming hematite schists and quartz-hematite schists.

6. As an alteration product of other iron minerals. The fibrous pencil-ore of England is supposed to be formed by the dehydration of limonite. Martite is a pseudomorph of hematite after octahedral crystals of magnetite.

Turyite, $Fe_2O_3(H_2O)_x$

Form. The typical occurrence of turyite (formerly called turgite) is in colloform crusts usually with a fibrous structure. It also occurs in massive forms. It is probably the amorphous equivalent of hematite.

H. = 5 to 6. **Sp. gr.** = 3.5–5.0.

Color, black to dark red. Streak, dark cherry-red.

Optical Properties. n, variable 2.4–2.6. Fragments are thin splinters which under crossed nicols in direct sunlight show a deep red color.

Chemical Composition. Ferric oxid with a variable amount of water, $Fe_2O_3(H_2O)_x$·(H_2O usually = 4 to 6 per cent.).

Blowpipe Tests. Fusible with difficulty. In the closed tube decrepitates and gives water.

Soluble in dilute HCl.

Distinguishing Features. Turyite is distinguished from hematite by the presence of water, and from goethite and limonite by its red streak.

Occurrence. 1. In the oxidized zone of various ore-deposits, often associated with goethite and limonite.

RUTILE GROUP—TETRAGONAL

Cassiterite (SnO_2) and rutile (TiO_2) together with plattnerite (PbO_2), polianite (MnO_2), zircon ($ZrSiO_4$ or $ZrO_2 \cdot SiO_2$), and thorite ($ThSiO_4$ or $ThO_2 \cdot SiO_2$) are isomorphous; all are tetragonal dioxids of tetravalent metals.

CASSITERITE, SnO_2

Form. Cassiterite is found in crystals, crystalline and reniform masses, pebbles, and grains (stream-tin). Crystals are tetragonal and prismatic or pyramidal in habit. Twins are common.

H. = 6½. **Sp. gr.** 7.0±.

Color, black or brown. Luster, adamantine.

Optical Properties. n_γ (2.09) − n_α(1.99) = 0.10. Double refraction strong. Fragments are irregular with high-order interference colors and high relief even in methylene iodid. Some varieties are pleochroic.

Chemical Composition. Tin oxid, SnO_2; (Sn = 78.6 per cent.).

Blowpipe Tests. Infusible. Fused with sodium carbonate, sulfur, and a little powdered charcoal gives a metallic button

and a straw-colored coating near the assay. The coating heated with $Co(NO_3)_2$ solution assumes a bluish-green color. Placed on zinc and treated with dilute HCl, the mineral gives a coating of tin, which takes a good polish when rubbed.

Insoluble in acids.

Distinguishing Features. The high specific gravity and adamantine luster serve to distinguish cassiterite from other minerals.

Uses. Cassiterite is practically the only source of tin. The Malay States lead in the production of tin, with Bolivia second.

Occurrence. 1. In tin-stone veins associated with topaz, wolframite, arsenopyrite, lepidolite, and fluorite. Granite is the country rock. Zinnwald, Bohemia, is a prominent locality.

2. In greisen (quartz-muscovite rock) and other rocks affected by the intrusion of pegmatites, but rare in the pegmatites themselves.

3. In rhyolites and quartz porphyries often accompanied by topaz. Durango, Mexico.

4. In sands and gravels. (Stream-tin).

Rutile, TiO_2

Form. Rutile is found in embedded grains or crystals, as acicular inclusions or in a massive form. Crystals are tetragonal and usually prismatic in habit. Usual forms: $p\{111\}$, $e\{101\}$, $a\{100\}$, $m\{110\}$. Interfacial angles: $pm(111 : 100) = 47° 40'$; $ea(101 : 100) = 57° 13'$; $ee(101 : 011) = 45° 2'$. Figures 433 to 436 represent various types of twinned crystals with $e\{101\}$ as twin-plane.

Cleavage. Imperfect prismatic.

H. = 6–6½. **Sp. gr.** 4.2±.

Color. Red, brownish-red to black. Streak, pale brown. Luster, metallic-adamantine.

Optical Properties. $n_\gamma(2.90) - n_\alpha(2.62) - 0.28$. Fragments are yellow and irregular with high-order interference colors and high relief even in methylene iodid.

Chemical Composition. Titanium oxide, TiO_2; (Ti = 60.0 per cent.). Iron is usually present.

Blowpipe Tests. Infusible. Gives a violet $NaPO_3$ bead in R.F. (Use very fine powder and first heat in O.F.)

Insoluble in acids.

Distinguishing Features. Distinguished from cassiterite by lower specific gravity. The red color and metallic-adamantine luster are distinctive.

Uses. Rutile is used as coloring matter for porcelain and as a source of ferro-titanium. Nelson County, Virginia, is an important locality.

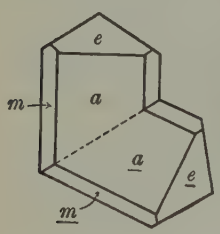


FIG. 433.

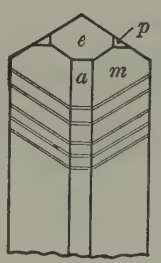


FIG. 434.

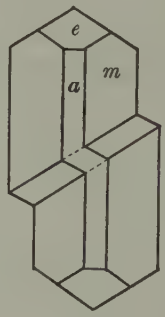


FIG. 435.

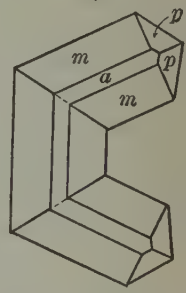


FIG. 436.

Occurrence. 1. As a constituent of high-temperature veins (or pegmatites) associated with apatite and scapolite. The country rock is gabbro. Kragerö, Norway.

2. As a secondary mineral in various rocks such as gneisses, schists, and clays. The rutile is set free by the decomposition of titanium-bearing silicates, especially the pyroxenes. Rutile is also an alteration product of titanite and occurs as a paramorph after brookite (an orthorhombic form of TiO_2).

Pyrolusite, $MnO_2 \cdot (H_2O)_x$

Form. Pyrolusite occurs in fibrous and columnar forms, in acicular crystals, in crusts, in masses, and along seams in den-

dritic forms. Crystals are prismatic but indistinct, and probably always pseudomorphous after manganite.

H. = 1 to 2. **Sp. gr.** 4.8±.

Color, black. Streak, black. Luster, metallic to dull. Opaque.

Chemical Composition. Manganese dioxid with a little adsorbed water, $MnO_2\ (H_2O)_x$; (Mn = 63.2 per cent.).

Blowpipe Tests. Infusible. In closed tube it gives a small amount of water (usually about 2 per cent.). Gives manganese bead tests.

Soluble in HCl with the evolution of chlorin.

Distinguishing Features. Distinguished from other manganese oxids by its inferior hardness and small water content.

Uses. Pyrolusite is one of the prominent ores of manganese, but it is usually mixed with psilomelane or manganite. It is also used in the manufacture of chlorin and has other minor uses.

Occurrence. 1. Pyrolusite is probably in most cases formed by the dehydration of manganite. Its occurrence is similar to that of the other manganese oxids. Hants county, Nova Scotia.

Stibiconite, $Sb_2O_4(H_2O)_x$

Form. Stibiconite occurs massive or as a coating. It is never found crystallized, but is sometimes pseudomorphous after stibnite.

H. = 4 to 5. **Sp. gr.** 5.2±.

Color, pale yellow. Luster, dull.

Optical Properties. n = 1.61–1.75. Fragments are irregular, color pale yellow, and isotropic.

Chemical Composition. Amorphous antimony tetroxid with adsorbed or dissolved water; $Sb_2O_4(H_2O)_x$ (Sb about 75 per cent.).

Blowpipe Tests. Infusible. In the closed tube gives water.

Insoluble in HCl.

Distinguishing Features. Stibiconite is recognized by its pale yellow color and high specific gravity. It is usually associated with stibnite.

Uses. A minor ore of antimony but abundant in certain localities.

Occurrence. 1. A secondary mineral often found with stibnite and resulting from its oxidation.

6. ALUMINATES, FERRITES, ETC.

Spinel,	$MgAl_2O_4$
MAGNETITE,	$FeFe_2O_4$
Franklinite,	$(Zn,Mn)Fe_2O_4$
CHROMITE,	$(Fe,Mg)(Cr,Al)_2O_4$
Hausmannite	Mn_3O_4

These minerals are sometimes considered as oxids, but they are probably salts of certain unfamiliar acids. Spinel is magnesium metaluminate derived from $HAlO_2(H_3AlO_3 - H_2O)$. Magnetite is ferrous metaferrite; iron acts both as an acid and as a base. Chromite is essentially ferrous metachromite, derived from $HCrO_2$ $(H_3CrO_3 - H_2O)$.

SPINEL GROUP—ISOMETRIC

Four of the enumerated minerals belong to the spinel group, which is one of the best known examples of isomorphism, for many intermediate compounds exist. The minerals of this group are isometric and usually crystallize in octahedrons. Besides the minerals mentioned there are also hercynite ($FeAl_2O_4$), gahnite ($ZnAl_2O_4$), and jacobsite ($MnFe_2O_4$). The general formula, then, is: $(Mg,Fe,Mn,Zn)(Al,Fe,Cr,Mn)_2O_4$. The following analyses illustrate the range and variation in composition.

Analyses of Minerals of the Spinel Group

	MgO	FeO	MnO	ZnO	Al_2O_3	Fe_2O_3	Mn_2O_3	Cr_2O_3	Misc.
Spinel	24.6	4.6	...	....	69.7	1.6	...		
Spinel pleonaste)	19.9	11.6	....	....	68.5	....	...		
Spinel (picotite)..	23.6	3.9	....	....	53.9	11.4	...	7.2	
Hercynite	2.9	35.7	....	....	61.2	....	...		
Magnetite	3.0	26.1	tr	....	....	70.6	...	....	TiO_2 = 0.3
Magnetite	2.1	27.7	0.4	....	1.1	68.5	...	0.6	
Gahnite	0.1	....	1.1	39.6	49.8	....	...	....	SiO_2 = 0.6
Franklinite	....	....	10.5	23.1	....	63.4	4.4	....	
Jacobsite	6.4	....	20.7	....	....	68.3	4.0	....	
Chromite	4.4	25.0	0.9	....	7.2	....	...	59.2	SiO_2 = 3.2
Chromite	14.1	18.0	0.5	....	12.1	....	...	56.5	

Spinel, $MgAl_2O_4$

Form. Spinel is practically always found in crystals or grains, usually disseminated, but sometimes loose in sands and gravels. Crystals are isometric, the octahedron being the only common form (Fig. 437). Contact-twins with {111} as twinning plane are so common that this twin-law is known as the spinel law (Fig. 438).

H. = 8. **Sp. gr.** 3.6 to 4.0, depending upon composition.

Color, black and dark shades of gray, brown, and green; also red and blue. Usually translucent. Luster, sub-adamantine.

Optical Properties. Isotropic. $n = 1.72$. Fragments are irregular and dark between crossed nicols. The usual color of the fragments is green (pleonaste) and coffee-brown (picotite).

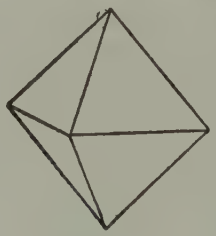


Fig. 437.

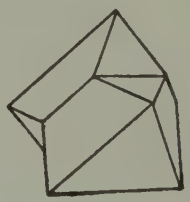


Fig. 438.

Chemical Composition. Magnesium metaluminate, $MgAl_2O_4$ or $MgO \cdot Al_2O_3$; (MgO = 28.2 per cent.). The magnesium is often replaced by ferrous iron, and the aluminum by chromium and ferric iron. The iron-bearing spinel is called pleonaste and the chrome-bearing spinel, picotite.

Blowpipe Tests. Infusible, but the color may change on heating. Turns blue when heated with cobalt nitrate solution.

Insoluble in hydrochloric and nitric acids. Decomposed by fusion with potassium acid sulfate.

Distinguishing Features. Distinguished from most minerals by its octahedral form and superior hardness. The black variety is distinguished from magnetite by its non-metallic luster

and non-magnetic character. From ruby, the red variety is distinguished by optical tests.

Uses. A red variety called spinel-ruby is used as a gem.

Occurrence. 1. As a contact mineral in crystalline limestone associated with phlogopite, chondrodite, corundum, and graphite. Amity, New York, is a prominent locality.

2. As an accessory mineral in various igneous and metamorphic rocks. Pleonaste occurs with emery, and picotite, with serpentine.

3. In gem-bearing gravels. (Ruby spinel.) Ceylon.

MAGNETITE, $FeFe_2O_4$ (or Fe_3O_4)

Form. Magnetite occurs in loose and attached crystals, in compact and granular masses, and in the form of sand. Crystals

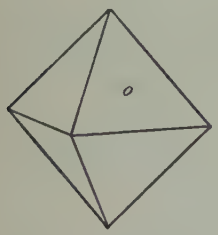


FIG. 439.

FIG. 440.

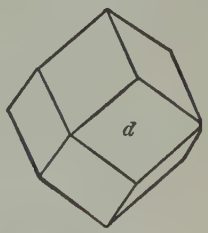


FIG. 441.

belong to the hexoctahedral class of the isometric system. The only common forms are the octahedron *o*, the dodecahedron *d*, and the trapezohedron *m*{311}. The habit is octahedral, more rarely dodecahedral, but almost never cubic. Figures 439, 440, and 441 represent typical crystals.

Cleavage. Some specimens have octahedral parting.

H. = 6. **Sp. gr.** 5.1±.

Color, black. Streak, black. Opaque. Luster metallic. Strongly attracted by the magnet and sometimes is a magnet itself (*lodestone*).

Chemical Composition. Ferrous metaferrite, $FeFe_2O_4$ or Fe_3O_4. (FeO = 31.0; Fe = 72.4 per cent.). May contain magnesium, manganese, or titanium.

Blowpipe Tests. Fusible with difficulty (5½). Gives bead tests for iron.

Soluble in concentrated HCl. The hydrochloric acid solution of the borax fusion gives tests for both ferrous and ferric iron.

Distinguishing Features. Magnetite is distinguished from all other black minerals by its strong magnetism. Hematite and chromite are often similar but are recognized by differences in streak.

Uses. Magnetite is an important ore of iron, mined in New York, New Jersey, and Pennsylvania, and in Scandinavia it is the principal iron ore.

Occurrence. 1. A very common and widely distributed accessory constituent of igneous rocks.

2. In ore-deposits due to magmatic segregation at the end of the magmatic period. The Scandinavian magnetite has this origin.

3. As a contact mineral between igneous rocks and limestones often occurring with pyrite and hematite.

4. In lenses and layers in schists and gneisses.

5. As an alteration product of iron-bearing silicates in more or less altered igneous rocks (serpentines, for example).

6. In detrital deposits as the main constituent of the so-called black sands which are prominent on the Pacific Coast.

Franklinite, $(Zn,Mn)Fe_2O_4$

Form. Franklinite occurs in disseminated crystals or in granular aggregates. The crystals are usually octahedrons, modified by the dodecahedron (like Fig. 426, p. 267).

H. = 6. **Sp. gr.** 5.1±.

Color, black. Opaque. Luster, metallic. Streak, dark brown. Slightly magnetic.

Chemical Composition. Zinc and manganese metaferrite,

$(Zn,Mn)Fe_2O_4$ or $(Zn,Mn)O \cdot Fe_2O_3$. Some analyses show ferrous iron and manganic manganese. A typical analysis is given on p. 277.

Blowpipe Tests. Infusible. In O.F. the borax bead is amethyst (Mn), while in R.F. it is green (Fe). On charcoal with sodium carbonate it gives a white coating of ZnO and a magnetic residue.

Soluble in HCl with the evolution of a little chlorin.

Distinguishing Features. Franklinite resembles magnetite and chromite, but may usually be distinguished by its association with willemite and zincite (a dark red mineral with the composition: ZnO).

Uses. Franklinite, extensively mined in Sussex county, New Jersey, is used for the production of zinc white. The residue is used for the production of spiegeleisen, an iron-manganese alloy.

Occurrence. 1. In crystalline limestone with willemite, zincite, and rhodonite. Sussex County, New Jersey, is practically the only locality for this mineral. This deposit was probably formed by the metamorphism of a sedimentary limestone containing calamine and some manganese mineral.

CHROMITE, $(Fe,Mg)(Cr,Al)_2O_4$

Form. Chromite occurs disseminated and in compact masses, rarely in small octahedral crystals.

H. = $5\frac{1}{2}$. **Sp. gr.** $4.4\pm$.

Color, black. Streak, dark brown. Luster, submetallic or metallic. Opaque. Some varieties are slightly magnetic on account of the presence of the magnetite molecule in solid solution.

Optical Properties. Isotropic $n > 1.93$. Thin fragments are irregular, usually translucent brown, and dark between crossed nicols.

Chemical Composition. Ferrous and magnesium metachro-

mite and metaluminate. Ferric iron may also be present. Two typical analyses are given on page 277.

Blowpipe Tests. Infusible. Gives chromium bead tests. Fused with sodium carbonate it gives a magnetic mass.

Insoluble in acids. Decomposed by sodium carbonate with the formation of sodium chromate, which is soluble in water.

Distinguishing Features. The submetallic luster is distinctive. It is usually associated with antigorite.

Uses. Chromite is the only source of the salts of chromium such as potassium chromate, potassium dichromate, and lead chromate. Chromite bricks are used as a furnace-lining for certain kinds of smelting. Ferro-chrome is an alloy used in making chrome-steel. New Caledonia and Rhodesia are the principal sources of chromite. Important deposits exist in California.

Occurrence. In peridotites and derived serpentines as an original or residual constituent. Ore deposits may be due to magmatic segregation. Woods mine, Lancaster county, Pennsylvania.

2. In serpentines, probably derived from chromium-bearing olivine in the process of the serpentinization of peridotite. Lake county, California.

Hausmannite, Mn_3O_4

Form. Hausmanite is usually a massive mineral but sometimes it occurs in euhedral tetragonal crystals with the tetragonal bipyramid {111} as the dominant form.

Cleavage, fairly distinct.

H = 5 to 5½. **Sp. gr.** 4.8±.

Color, steel gray to brownish, reddish black streak, chestnut brown, luster submetallic.

Optical Properties $n_\gamma(2.45) - n_\alpha(2.15) = 0.30$ (Larsen). Fragments are dark red and doubly refracting when examined in direct sunlight between crossed nicols.

Chemical Composition, probably a manganese manganite, $MnMn_2O_4$ (= Mn_3O_4). Mn = 72 per cent.

Blowpipe Tests. Infusible. It gives the Mn bead tests. Soluble in HCl with the evolution of chlorin.

Distinguishing Features. It is distinguished from the manganese dioxide minerals by its streak and absence of water.

Uses. Hausmannite is one of the minor ores of manganese. It has been mined at Batesville, Arkansas.

Occurrence. 1. A hydrothermal replacement of limestone. Often altered to psilomelane.

7. HYDROXIDS

Goethite,	$Fe_2O_3 \cdot H_2O$
Manganite,	$Mn_2O_3 \cdot H_2O$
LIMONITE,	$H_2Fe_2O_4(H_2O)_x$
Gibbsite,	$Al(OH)_3$
CLIACHITE,	$Al_2O_3(H_2O)_x$
Brucite,	$Mg(OH)_2$
PSILOMELANE,	$4MnO_2 \cdot (Ba,K_2)O \cdot (H_2O)_x(?)$

The hydroxids or hydrous oxides are in part normal hydroxids such as $Mg(OH)_2$. Others may be derived by subtracting water from the normal compounds. For example, $2Fe(OH)_3 - 2H_2O = Fe_2O_3 \cdot H_2O$, goethite.

Goethite, $Fe_2O_3 \cdot H_2O$

Form. Goethite is found in small acicular crystals, in bladed crystal aggregates, and in scaly or fibrous masses. Crystals are orthorhombic, but are usually too minute to decipher.

Cleavage, in one direction parallel to the length.

H. = 5½. **Sp. gr.** 4.3±.

Color, yellowish-brown to nearly black. Streak, yellowish-brown like that of limonite. Luster, metallic-adamantine.

Optical Properties. $n_\gamma(2.40) - n_\alpha(2.26) = 0.14$. Thin fragments are prismatic, and translucent brown with parallel extinction.

Chemical Composition. Ferric oxid monohydrate, $Fe_2O_3 \cdot H_2O$ ($H_2O = 10.1$ per cent.). It usually contains a little manganese. Fibrous varieties contain an excess of water over that required by the formula.

Blowpipe Tests. Fusible with difficulty (5½). In the closed tube turns red and gives off water. Bead tests for iron.

Soluble in HCl.

Distinguishing Features. The yellow-brown streak and fibrous or bladed structure are distinctive. It is distinguished from limonite by the fact that it is crystalline.

Uses. As an ore of iron it is classed as brown hematite along with limonite.

Occurrence. 1. In iron-ore deposits along with limonite and hematite.

2. As inclusions in various minerals such as feldspars, quartz, etc.

Manganite, $Mn_2O_3 \cdot H_2O$

Form. Manganite is found in prismatic crystals and in columnar and fibrous masses. Crystals are orthorhombic, prismatic in habit, and striated parallel to their length.

Cleavage, in one direction (010) parallel to the length of the crystals.

H. = 4. **Sp. gr.** 4.3±.

Color. Iron-black or dark gray. Streak, dark brown. Luster, submetallic. Opaque.

Chemical Composition. Manganic oxid monohydrate $Mn_2O_3 \cdot H_2O$; (H_2O = 10.3 per cent.).

Blowpipe Tests. Infusible. In the closed tube gives water. Bead tests for manganese.

Soluble in HCl with the evolution of chlorin.

Distinguishing Features. Manganite is distinguished from psilomelane by its crystalline structure and inferior hardness, and from pyrolusite by its greater hardness, brown streak, and higher water content.

Uses. Manganite is an ore of manganese occurring along with pyrolusite and psilomelane.

Occurrence. 1. As a vein mineral. Ilefeld in the Harz Mts. is a prominent locality.

2. As a secondary mineral in residual clays associated with psilomelane.

LIMONITE, $H_2Fe_2O_4(H_2O)_x$

Form. Limonite occurs in colloform crusts and in compact, pisolitic, nodular, porous, and earthy masses. It is often pseudomorphous after other iron minerals, especially pyrite.

H. = 5½. **Sp. gr.** 3.8±.

Color, yellow, brown, or black. Streak, yellowish-brown. Luster, submetallic to dull.

Optical Properties. n = 2.0 − 2.1. Fragments are irregular, and either isotropic or doubly refracting.

Chemical Composition. Ferric hydroxid, $H_2Fe_2O_4(H_2O)_x$ (Fe= 50 to 60 per cent.). (H_2O = 13 to 18 per cent.). Often impure from the presence of manganese oxid, phosphates, clay, sand, and organic matter.

Blowpipe Tests. Fusible with difficulty (5½). When heated in R.F. it becomes magnetic. In the closed tube it turns red and yields water. Iron bead tests.

Soluble in HCl.

Distinguishing Features. Limonite is distinguished from hematite by its red streak and from goethite by the absence of fibrous structure and by its optically isotropic character.

Uses. Limonite is a prominent ore of iron and in the United States ranks next to hematite in importance.

Occurrence. 1. As a secondary mineral in veins and ore deposits formed by the oxidation of pyrite. It constitutes an important part of the gossan or "iron-hat."

2. As a metasomatic replacement of limestone.

3. As sedimentary bedded deposits, often with an oolitic structure and perhaps formed from original oolitic siderite. The "minette" ores of Lorraine and Luxembourg belong here.

4. As bog iron ore formed by the oxidation of $FeH_2(CO_3)_2$ in solution in marshes (probably by iron bacteria).

5. As a pigment and stain in various rocks.

Gibbsite (Hydrargillite) $Al(OH)_3$

Form. Gibbsite occurs in minute pseudohexagonal crystals often lining cavities and in stalactitic and incrusting forms. In

thin sections it is sometimes seen as a crystalline aggregate pseudomorphous after feldspars.

Cleavage in one direction.

H. = 2½ to 3½. **Sp. gr.** 2.4±.

Color. Colorless, white, gray, and pale colors.

Optical Properties. $n_\gamma(1.558) - n_\alpha(1.535) = 0.023$. Fragments are platy or prismatic to acicular with oblique extinction. The inference colors vary from first-order gray up to lower second-order.

Chemical Composition. Aluminum hydroxid, $Al(OH)_3$; (H_2O = 34.6 per cent.).

Blowpipe Tests. Infusible. When heated with cobalt nitrate solution it becomes blue. In the closed tube yields water. Insoluble in dilute HCl.

Uses. Gibbsite is one of the constituents of bauxite, which is used as a source of aluminum and aluminum salts.

Distinguishing Features. Some varieties resemble chalcedony from which it is distinguished by inferior hardness. Gibbsite is crystalline, while cliachite is amorphous.

Occurrence. 1. Occurs along with cliachite in bauxite, a rock produced from clay by desilication. Bauxite, Arkansas.

2. Occurs in limonitic iron ores. Clove mine. Dutchess county, New York.

CLIACHITE, $Al_2O_3 \cdot (H_2O)_x$

Forms. Cliachite is an amorphous mineral which is the principal constituent of the rock called bauxite. It occurs in pisolitic forms, more rarely in clay-like masses. The crystalline equivalent of cliachite is gibbsite ($Al(OH)_3$).

H. = 1 to 3. **Sp. gr.** 2.5±.

Color, white, yellowish-white, pale red, or brownish-red. Luster, dull and earthy.

Optical Properties. n about 1.57. Fragments are irregular and isotropic. Associated doubly-refracting particles are usually gibbsite.

Chemical Composition. Hydrous aluminum oxid, Al_2O_3-$(H_2O)_x$. Cliachite often contains iron (up to 15 per cent.).

Blowpipes Tests. Infusible. Heated intensely with cobalt nitrate solution it becomes blue. In the closed tube gives abundant water. If pure, it completely dissolves in the $NaPO_3$ bead, while clay, on the other hand, leaves a residue of silica.

Soluble in HCl with difficulty.

Distinguishing Features. Cliachite is easily recognized on account of the pisolitic structure. The clay-like variety can only be distinguished by proving the absence of silica.

Uses. Bauxite is now practically the only ore of aluminum. It is mined in Georgia, Alabama, Arkansas, and Tennessee. Bauxite is also used in the production of aluminum salts, aluminum oxid (used as an abrasive), and for bauxite bricks.

Occurrence. 1. Cliachite is the principal constituent of bauxite, a rock produced by the desilication of clays, which in Arkansas were formed from nepheline syenites.

Brucite, $Mg(OH)_2$

Form. Brucite is occasionally found in crystals, but more often in foliated masses and sometimes in fibrous seams. Crystals are hexagonal and tabular in habit with the basal pinacoid and several rhombohedrons.

Cleavage, in one direction parallel to (0001).

H. = 2½. **Sp. gr.** ±2.4.

Color, white or greenish-white. Luster, pearly or silky.

Optical Properties. $n_\gamma(1.58) - n_\alpha(1.56) = 0.02$. Cleavage flakes give a positive uniaxial interference figure without rings unless very thick. The fibrous variety gives acicular fragments with parallel extinction and negative elongation.

Chemical Composition. Magnesium hydroxid, $Mg(OH)_2$ or $MgO \cdot H_2O$; (H_2O = 31.0 per cent.). It often contains iron and manganese. The manganese is due to the isomorphous replacement of $Mn(OH)_2$. The latter occurs as a mineral called pyrochroite.

Blowpipe Tests. Infusible, but glows. Heated with cobalt nitrate solution it turns pink. In the closed tube yields water and becomes opaque.

Soluble in HCl.

Distinguishing Features. Distinguished from gypsum by its fusibility and absence of calcium. Its occurrence is characteristic.

Occurrence. 1. As a secondary mineral in serpentine often associated with magnesite and dolomite. Texas, Pennsylvania, is a prominent locality.

2. In crystalline limestones associated with chondrodite and spinel. It has been produced by the hydration of periclase (MgO). Crestmore, Riverside County, California.

PSILOMELANE, $4MnO_2 \cdot (Ba,K_2)O \cdot (H_2O)_x$?

Form. Amorphous. Psilomelane is usually a compact massive or earthy mineral without any hint of crystalline structure. Occasionally it shows a colloform surface in open spaces.

H. = 3 to 6. **Sp. gr.** 3.0–4.5.

Color, black to brown. Streak, brownish-black to brown. Luster, submetallic to dull. Opaque.

Chemical Composition. Impure hydrous manganese dioxid, perhaps $4MnO_2 \cdot (Ba,K_2)O \cdot H_2O$; ($MnO_2$ = 70 to 90 per cent. H_2O = 3 to 9 per cent.). It usually contains barium and potassium and sometimes lithium, cobalt, copper, or iron.

Blowpipe Tests. Infusible. In the closed tube gives water and also oxygen. Manganese bead tests.

Soluble in HCl with the evolution of chlorin.

Distinguishing Features. Distinguished from pyrolusite and manganite by the absence of crystalline structure and from limonite by the streak.

Uses. Psilomelane is an important ore of manganese and is also used as a source of chlorin. An earthy cobalt-bearing variety (asbolane) is used as a source of cobalt compounds.

Occurrence. 1. In residual clays formed during the process of weathering. Batesville, Arkansas.

2. In bog deposits often associated with limonite.

8. CARBONATES

A. Normal Anhydrous Carbonates

Calcite Group	CALCITE,	$CaCO_3$
	DOLOMITE,	$CaMg(CO_3)_2$
	Magnesite,	$MgCO_3$
	SIDERITE,	$FeCO_3$
	Rhodochrosite,	$MnCO_3$
	SMITHSONITE,	$ZnCO_3$
Aragonite Group	Aragonite,	$CaCO_3$
	Strontianite,	$SrCO_3$
	Witherite,	$BaCO_3$
	CERUSSITE,	$PbCO_3$

B. Basic Carbonates

MALACHITE,	$Cu_2(OH)_2CO_3$
Azurite,	$Cu_3(OH)_2(CO_3)_2$
Hydromagnesite,	$Mg_4(OH)_2(CO_3)_3 \cdot 3H_2O$

The carbonates are not many in number, but they include some of the most common minerals with which the mineralogist has to deal. All the important normal carbonates fall into two well-defined isomorphous groups: the calcite group (rhombohedral) and the aragonite group (orthorhombic). These two groups are said to be isodimorphous, as calcite and aragonite are dimorphous.

CALCITE GROUP—HEXAGONAL

The calcite group of rhombohedral carbonates is a well characterized group of familiar minerals. These minerals crystallize in rhombohedral and scalenohedral crystals with cleavage parallel to the faces of a rhombohedron of about 75°. All except dolomite belong to the ditrigonal scalenohedral class of the hexagonal system. Dolomite belongs to the rhombohedral class, but is similar to the other minerals in angles and other properties. All the minerals of this group are uniaxial and optically negative, and

have very strong double refraction. Many isomorphous mixtures are known; and some of them have received special names (see breunnerite, ankerite, and mesitite below).

The following analyses are representative of the minerals mentioned and illustrate isomorphism.

	CaO	MgO	FeO	MnO	ZnO	CO_2	Misc.
Calcite	56.0	....	0.4	....	....	43.5	H_2O = 0.1
Calcite	48.7	0.9	0.4	6.8	0.4	40.8	H_2O = 0.3
Dolomite	31.4	21.2	....	....	....	47.7	
Dolomite	29.6	17.6	6.7	....	....	45.6	
Dolomite (Ankerite)	28.4	10.2	17.2	....	....	44.2	
Magnesite	....	47.3	0.8	....	....	51.5	H_2O = 0.5
Magnesite (Breunnerite)	....	41.8	6.5	0.6	....	50.3	
Magnesite (Mesitite)	1.3	28.1	24.2	....	....	45.8	
Siderite	0.2	....	59.6	1.9	....	38.0	
Siderite	....	2.4	50.4	7.5	....	38.6	gangue = 0.3
Rhodochrosite	0.6	0.4	0.4	59.9	....	38.3	
Smithsonite	0.4	....	0.1	....	64.1	34.7	CdO = 0.6; CdS = 0.3

CALCITE, $CaCO_3$

Calcite has played a very prominent part in the history of mineralogy. The discovery of cleavage in calcite led to the establishment of crystallography as an exact science by Haüy, and the discovery of double refraction in calcite led to the development of crystal optics. The invention of the Nicol prism, which is made of calcite, has made possible the identification of fine-grained mineral aggregates and rocks.

Form. Calcite is found in well defined crystals (often large in size), in crystalline crusts and druses, in cleavable masses, in various imitative forms, such as stalactitic, pisolitic, and oölitic, in granular masses, and sometimes in fibrous forms.

Calcite is the type example of the ditrigonal scalenohedral class of the hexagonal system. In number of forms and variety of their combinations, calcite is unsurpassed among minerals. Over 300 well established forms, most of them rhombohedrons and scalenohedrons, are known. $\dot{c} = 0.854$.

Usual forms (in order of their abundance): $m\{10\bar{1}0\}$, $c\{0001\}$, $e\{01\bar{1}2\}$, $f\{02\bar{2}1\}$, $r\{10\bar{1}1\}$, $M\{40\bar{4}1\}$, $v\{21\bar{3}1\}$, $a\{11\bar{2}0\}$, $y\{32\bar{5}1\}$, $t\{21\bar{3}4\}$.

Interfacial angles: $ee(01\bar{1}2:\bar{1}012) = 45°\ 3'$; $em\{01\bar{1}2:10\bar{1}0\} = 63°\ 45'$; $rr(10\bar{1}1:\bar{1}101) = 74°\ 55'$; $rm(10\bar{1}1:10\bar{1}0) = 45°\ 23\frac{1}{2}'$; $ff(02\bar{2}1:\bar{2}021) = 101°\ 9'$; $fm(02\bar{2}1:01\bar{1}0) = 26°\ 53'$; $MM(40\bar{4}1:4401) = 114°\ 10'$; $Mm(40\bar{4}1:10\bar{1}0 = 14°\ 13'$; $vv(21\bar{3}1:\bar{2}3\bar{1}1) = 75°\ 22'$; $vv(21\bar{3}1:3\bar{1}\bar{2}1) = 35°\ 36'$; $vv(21\bar{3}1:12\bar{3}\bar{1}) = 47°\ 1'$; $rv(10\bar{1}1:21\bar{3}1) = 29°\ 6\frac{1}{2}'$; $mv(10\bar{1}0:21\bar{3}1) = 28°\ 4'$; $yy(32\bar{5}1:5\bar{2}31) = 45°\ 32'$; $yy(32\bar{5}1:\bar{3}5\bar{2}1) = 70°\ 59'$; $tt(2\bar{1}34:\bar{2}3\bar{1}4) = 41°\ 55'$; $tt(21\bar{3}4:3\bar{1}\bar{2}4) = 20°\ 36\frac{1}{2}'$; $mm(10\bar{1}0:01\bar{1}0) = 60°\ 0'$; $ma(10\bar{1}0:11\bar{2}0) = 30°\ 0'$.

Fig. 442.

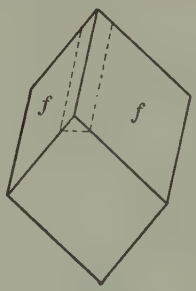


Fig. 443.

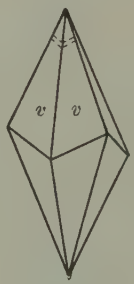


Fig. 444.

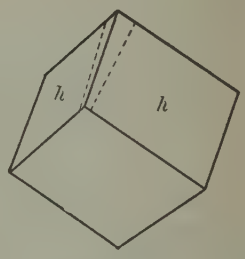


Fig. 445.

Figures 442–461 represent typical calcite crystals. These figures illustrate the great variation in habit. The habit is variable. Figures 442–445 are simple forms. Figure 442, $e\{01\bar{1}2\}$, is an obtuse rhombohedron, while Fig. 443, $f\{02\bar{2}1\}$, is an acute rhombohedron. Figure 445 is a pseudo-cubic rhombohedron $h\{03\bar{3}2\}$ with the angle hh $(03\bar{3}2:3\bar{3}02) = 91°\ 42'$. The dotted lines in each case represent the cleavage which is a great help in orienting a crystal. The unit rhombohedron $r\{10\bar{1}1\}$ alone is rare, but it is very frequently the dominant form as in Figs. 446 and 447. The combination em (Figs. 448 and 449) is said to be the most frequent combination. Figures 450–453 are common types. The bottom of Fig. 451

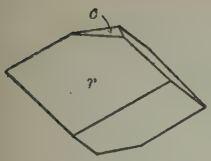


Fig. 446.

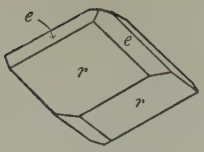


Fig. 447.

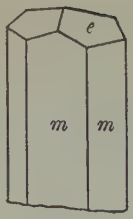


Fig. 448.

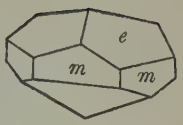


Fig. 449.

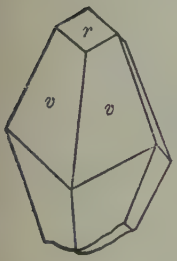


Fig. 450.

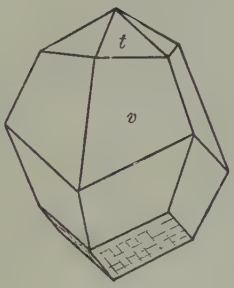


Fig. 451.

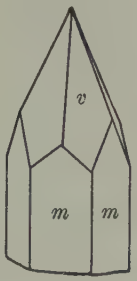


Fig. 452.

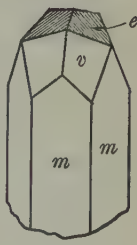


Fig. 453.

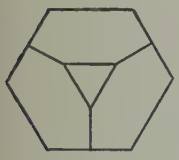


Fig. 454.

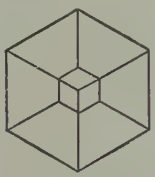


Fig. 455.

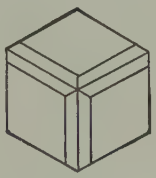


Fig. 456.

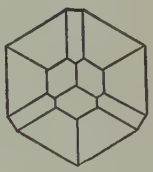


Fig. 457.

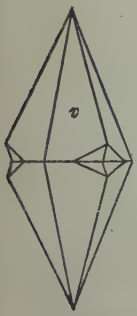


Fig. 458.

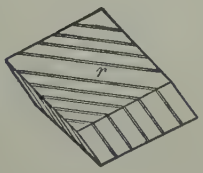


Fig. 459.

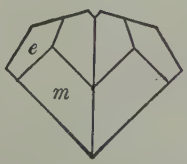


Fig. 460.

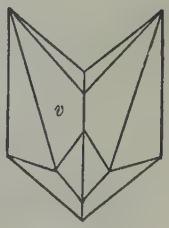


Fig. 461.

Figs. 446–461.—Calcite crystals.

represents cleavage. The faces of $e\{01\bar{1}2\}$ are very often striated as in Fig. 453. Figures 454 to 457 represent plans of common types of calcite crystals. The trigonal symmetry is apparent.

Five twinning laws are known for calcite. (1) {0001} as twin-plane. Figure 458 represents a scalenohedron twinned according to this law. (2) $\{01\bar{1}2\}$ as twin-plane. This is often polysynthetic twinning with striations parallel to the long diagonal (Fig. 459). 3. $\{10\bar{1}1\}$ as twin-plane. Figure 460 represents the combination $\{10\bar{1}0\}$, $\{01\bar{1}2\}$ twinned according to this law. The vertical axes of the two parts of the crystal are almost at right angles. (4) $\{02\bar{2}1\}$ as twin-plane. This is represented by Fig. 461. (5) $\{20\bar{2}1\}$ as twin-plane. This twinning law is very rare.

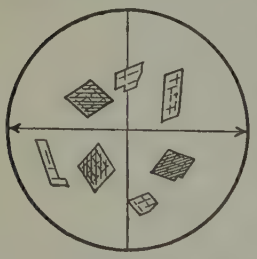


Fig. 462.—Cleavage fragments of calcite.

Cleavage, perfect rhombohedral in three directions at angles of 74° 55′. There is often parting parallel to $\{01\bar{1}2\}$ and this is sometimes better developed than the cleavage itself.

H. = 3. **Sp. gr.** 2.72±.

Color. Calcite is usually colorless, white, or amber, but may be any color. Luster, vitreous.

Optical Properties. $n_\gamma(1.658) - n_\alpha(1.486) = 0.172$. The strong double refraction is one of the most prominent characters of calcite. It may be observed in Iceland spar, the clear transparent cleavable variety. Fragments are rhombic (Fig. 462) with symmetrical extinction and very high-order interference colors. The rhombs often have striations parallel to the long diagonal. These are due to polysynthetic twinning produced by pounding the fragments. The relief varies with the direction. As shown in Fig. 462, the rhombs have a high relief when the long diagonal is parallel to the vibration plane of the lower nicol. It gives the microchemical gypsum test with dilute H_2SO_4 (Fig. 4, p. 43).

Chemical Composition. Calcium carbonate, $CaCO_3$; (CaO =

56.0 per cent.). The common replacing elements are iron, magnesium, and manganese. The amber color is due to a small amount of organic matter. Clay, sand, bitumen, and other mechanical impurities may be present.

Blowpipe Tests. Infusible, glows, and gives a yellowish-red flame coloration. In the closed tube whitens, gives off CO_2, and leaves a residue of CaO.

Easily soluble in large fragments in cold dilute HCl with vigorous effervescence. In concentrated solutions, dilute H_2SO_4 gives a white crystalline precipitate ($CaSO_4 \cdot 2H_2O$).

Distinguishing Features. Calcite is distinguished from dolomite by its lower specific gravity and by its ready effervescence in cold HCl. The colored varieties are distinguished from siderite and rhodocrosite by lower specific gravity. From aragonite it is distinguished by perfect rhombohedral cleavage and by its failure to give a lilac color when heated in a test-tube with cobalt nitrate solution.

Uses. Limestones are extensively used for building and ornamental stones, in the manufacture of cement, as ballast and road material and as a flux in smelting. Iceland spar is used in optical apparatus, especially the polarizing microscope.

Occurrence. 1. As a vein mineral, often forming the gangue of ores. The north of England furnishes fine crystallized specimens of calcite.

2. As travertine, calcareous tufa, and cave-deposits (stalactites and stalagmites). Calcium carbonate is soluble in carbonated water, and on the escape of CO_2, due to release of pressure, calcite crystallizes out.

3. As a biogenic mineral forming limestones, organisms such as molluscs, brachiopods, corals, and crinoids contributing their shells or other hard parts.

4. As a characteristic mineral in cavities of the basic igneous rocks, especially basalt, and often associated with the zeolites. Iceland spar occurs in large cavities in basalt in Iceland.

5. As a prominent mineral in seams and cavities of sedimentary

rocks, especially limestone. In the Joplin district fine amber-colored calcite crystals occur in chert breccias in the zinc mines along underground water courses. Crystal Cave at Joplin is completely lined with calcite crystals from 1 to 2 feet in length. It is probable that the calcite was formed when the cave was completely filled with a water solution of calcium carbonate.

6. As the principal constituent of crystalline limestones, which were formed from sedimentary limestones by metamorphism. The crystalline limestones often contain diopside, tremolite, wollastonite, garnet, spinel, graphite, etc.

7. As a paramorph after aragonite. Calcite is the stable form of calcium carbonate under ordinary conditions.

DOLOMITE, $Ca(Mg,Fe)(CO_3)_2$

Form. Dolomite is found in crystals, in crystal druses, in cleavable masses, and in granular and massive forms.

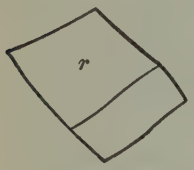


Fig. 463.

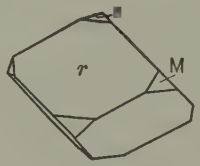


Fig. 464.

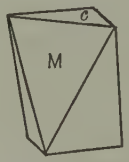


Fig. 465.

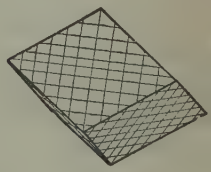


Fig. 466.

The crystals belong to the rhombohedral class of the hexagonal system and have a lower grade of symmetry than calcite crystals, though this is not often apparent on inspection. The only common kind of dolomite crystal is the simple unit rhombohedron, often curved and more or less saddle-shaped (Fig. 463). Figure 464 is a rhombohedron modified by $c\{0001\}$ and $M\{40\bar{4}1\}$. Crystals like Fig. 465 with $c\{0001\}$ and $M\{40\bar{4}1\}$ are found embedded in anhydrite and gypsum.

Several twinning laws are known for dolomite, but the only common one is polysynthetic twinning with $\{02\bar{2}1\}$ as twin-plane which gives rise to striations on the cleavage faces parallel to

both the short diagonal and the long diagonal of the rhomb (Fig. 466). This test can often be used to distinguish dolomite from calcite in crystalline limestones.

Cleavage, rhombohedral like that of calcite, but often curved. **H.** = 3½ to 4. **Sp. gr.** = 2.83 – 3.00 (varies with iron content).

Color, white, pink or gray, but rarely colorless. Luster, pearly or vitreous. It is often called *pearl spar.*

Optical Properties. $n_\gamma(1.682) - n_\alpha(1.503) = 0.179$. Double refraction very strong. Fragments are rhombic with symmetrical extinction and very high-order interference colors. The relief varies with the direction as in calcite. It gives the microchemical gypsum test with dilute H_2SO_4. In fragments it is distinguished from calcite by the absence of striations parallel to the long diagonal.

Chemical Composition. Calcium magnesium carbonate, $CaMg(CO_3)_2$; (For normal dolomite CaO = 30.4 per cent.; Mg = 21.7 per cent. $MgCO_3$ = 45.6). It often contains iron. The highly ferriferrous variety is known as *ankerite.* Ferriferous varieties are represented by the formula $Ca(Mg,Fe)(CO_3)_2$. Analyses are given on page 291.

Dolomite is a double salt with equal molecular quantities of $CaCO_3$ and $MgCO_3$, and not an isomorphous mixture of these two compounds.

Blowpipe Tests. Infusible and colors the flame yellowish red. The iron-bearing varieties darken in the closed tube and also become magnetic when heated in R.F. on charcoal.

Large fragments are only slightly attacked by cold dilute HCl. (Dolomite can thus be distinguished from calcite.) In concentrated solutions dilute H_2SO_4 gives a white crystalline precipitate.

Distinguishing Features. The curved unit rhombohedral crystals and pearly luster usually distinguish dolomite from calcite. Rhodochrosite is heavier than pink dolomite.

Uses. Dolomitic limestones, like ordinary limestones, are

used for building and ornamental purposes, and also for furnace linings.

Occurrence. 1. As a characteristic mineral in cavities of limestones. The pink dolomite of the Joplin district is a prominent example of this occurrence.

2. As the essential constituent of dolomitic or magnesian limestones. These limestones are formed from ordinary limestones by the process known as dolomitization. This consists of the partial replacement of calcium carbonate by magnesium carbonate in a way not fully understood. As there is a shrinkage of about 10 per cent., these dolomitic limestones are often porous.

3. As a vein mineral often associated with calcite, as in the north of England.

4. As the principal constituent of the crystalline dolomitic limestones. These consist either of dolomite or of a mixture of dolomite and calcite. Other characteristic minerals are tremolite, phlogopite, chondrodite, forsterite, spinel, antigorite, and talc. Antigorite and talc are secondary minerals formed from the other silicates.

Magnesite, $MgCO_3$

Form. Magnesite occurs in cleavable or compact porcelain-like masses. The so-called amorphous magnesite is microcrystalline (metacolloid) and sometimes has a colloform surface. Euhedral crystals of magnesite are exceedingly rare.

Cleavage. Rhombohedral cleavage is sometimes prominent.

Color, usually white or gray. Luster, vitreous to dull.

H. = 4 to 5½. **Sp. gr.** 3.1±.

Optical Properties. $n_\gamma(1.717) - n_\alpha(1.515) = 0.202$. Fragments are rhombic with symmetrical extinction, or irregular with aggregate structure. The interference colors are very high-order.

Chemical Composition. Magnesium carbonate, $MgCO_3$; (MgO = 47.6 per cent.). Iron and calcium are often present in small amounts. The massive varieties often contain magnesium silicate.

Blowpipe Tests. Infusible. Turns pink when heated with cobalt nitrate solution.

Soluble in hot HCl with effervescence.

Distinguishing Features. Magnesite is usually distinguished by the compact white masses, but some varieties show good cleavage and are distinguished by the comparatively high specific gravity. It may be necessary to prove that calcium is not an essential constituent.

Uses. Dead-burned magnesite is used as a refractory lining. The light-burned or caustic magnesite is used as a plaster and in the manufacture of wood pulp. Austria-Hungary and Greece are the principal producers of magnesite.

Occurrence. 1. In veins in serpentine (compact massive variety). Numerous localities in California.

2. In beds as a replacement of limestone or dolomite (cleavable variety). Stevens county, Washington.

SIDERITE, $FeCO_3$

Form. Siderite is found in small crystals in cavities, in cleavable masses, in colloform crusts, and in compact masses.

The crystals are varied in habit; the common forms are the unit rhombohedron ($10\bar{1}1 : \bar{1}101 = 73° 2\frac{1}{2}'$), the rhombohedron $\{01\bar{1}2\}$, and the rhombohedron $\{02\bar{2}1\}$, the latter often modified by the pinacoid $\{0001\}$. Figure 467 is the unit rhombohedron $r\{10\bar{1}1\}$. Crystals may be curved like those of dolomite.

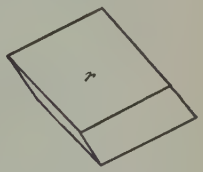


FIG. 467.

Cleavage, rhombohedral, like that of calcite.

H. = $3\frac{1}{2}$ to 4. **Sp. gr.** 3.8±.

Color, various tints and shades of brown and gray.

Optical Properties. $n_\gamma(1.87) - n_\alpha(1.63) = 0.24$. Strong double refraction. Fragments are rhombic with symmetrical extinction and very high-order interference colors. In methylene iodid the relief changes with the direction, but in both positions the index of refraction is greater than that of methylene iodid.

Chemical Composition. Ferrous carbonate, $FeCO_3$; (FeO = 62.1 per cent.). Calcium, magnesium, and manganese are usually present in small amounts as replacing elements. Clay-ironstone is an impure massive siderite containing argillaceous material.

Blowpipe Tests. Fuses with difficulty. In the closed tube it darkens. Heated on charcoal in R.F. it becomes magnetic.

It is soluble in hot HCl with effervescence and the solution gives tests for ferrous iron.

Distinguishing Features. Siderite is distinguished from brown calcite by its comparatively high specific gravity, and from sphalerite by its rhombohedral cleavage and vitreous luster.

Uses. Siderite is one of the minor ores of iron. The clay-ironstone variety has been mined extensively in England and to some extent in Ohio, Pennsylvania, and Maryland.

Occurrence. 1. As a vein mineral, often the gangue of other ores.

2. As a metasomatic replacement of limestone.

3. As "clay-ironstone" concretions in shales and as "black-band" ore, a carbonaceous variety.

4. As a secondary mineral in cavities of basalt.

Rhodochrosite, $MnCO_3$

Form. Rhodochrosite occurs in rhombohedral crystals and in cleavable masses. The unit rhombohedron with $(10\bar{1}1 : \bar{1}101) = 73° 0'$ is the only common kind of crystal (Fig. 468).

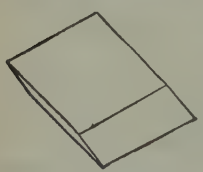


Fig. 468.

Cleavage, rhombohedral, like that of calcite.

H. = 4. **Sp. gr.** 3.5±.

Color, pink, red, brownish-red or reddish-gray.

Optical Properties. $n_\gamma(1.82) - n_\alpha(1.60) = 0.22$. Double refraction strong. Fragments are rhombic with symmetrical extinction and have very high-order interference colors.

Chemical Composition. Manganous carbonate, $MnCO_3$; (MnO = 61.7 per cent.). Calcium and iron are usually present as replacing elements.

Blowpipe Tests. Infusible. In the closed tube it darkens and decrepitates. The borax bead in O.F. is amethyst color.

Soluble in hot HCl with effervescence.

Distinguishing Features. Rhodochrosite is distinguished from pink calcite and dolomite by its higher specific gravity. It even more resembles rhodonite ($MnSiO_3$) but is distinguished by its rhombohedral cleavage and inferior hardness.

Uses. Rhodochrosite is sometimes an ore of manganese.

Occurrence. 1. A characteristic vein mineral often serving as the gangue of silver ores. Lake county, Colorado.

SMITHSONITE, $ZnCO_3$

Form. Smithsonite usually occurs in colloform incrustations and in porous masses. Crystals of smithsonite are comparatively rare and as a rule are much rounded.

Cleavage, imperfect rhombohedral and often curved.

H. = 5. **Sp. gr.** 4.4±.

Color, white, gray, yellow, brown; sometimes blue or green.

Optical Properties. $n_\gamma(1.82) - n_\alpha(1.62) = 0.20$. Strong double refraction. Fragments are rhombic with symmetrical extinction and very high-order interference colors. The index of refraction is greater than that of methylene iodid.

Chemical Composition. Zinc carbonate, $ZnCO_3$; (ZnO = 64.8 per cent.; Zn = 52.1 per cent.). Iron is the most frequent replacing element.

Blowpipe Tests. Infusible. Heated with cobalt nitrate solution on charcoal, it gives a green coating. In the closed tube it turns yellow.

Soluble in HCl with effervescence.

Distinguishing Features. It resembles calamine but is distinguished by the absence of crystals with sharp edges. It is harder than the other carbonates.

Uses. Smithsonite is one of the minor ores of zinc and is often associated with calamine, a basic zinc silicate. It is called "dry-bone" in the Wisconsin-Illinois-Iowa zinc district.

Occurrence. 1. Usually found in the oxidized zone and formed from sphalerite. It also occurs as a metasomatic replacement of limestone, and is often pseudomorphous after calcite and dolomite. Marion county, Arkansas, is a prominent locality.

ARAGONITE GROUP—ORTHORHOMBIC

The aragonite group is an isomorphous group consisting of aragonite $CaCO_3$; strontianite, $SrCO_3$; witherite, $BaCO_3$; and cerussite, $PbCO_3$. The crystals are orthorhombic, but pseudohexagonal ($110 : 1\bar{1}0 = 62° - 64°$), and are usually prismatic in habit. Twinning on the unit prism {110} is very common and also accounts for the pseudohexagonal character of some crystals. Optically the minerals are biaxial with a small axial angle. The double refraction is very strong as in the calcite group.

Aragonite, $CaCO_3$

Form. Aragonite occurs in acicular crystals, in columnar and fibrous masses, and in incrusting and stalactitic forms. Fibrous masses are especially common for aragonite.

The crystals are usually prismatic or acicular in habit, and belong to the bipyramidal class of the orthorhombic system. Usual forms: $m\{110\}$, $b\{010\}$, $k\{011\}$. Interfacial angles: $mm(110 : 1\bar{1}0) = 63°\ 48'$; $mb(110 : 010) = 58°\ 6'$; $bk(010 : 011) = 54°\ 13\frac{1}{2}'$. Figures 469 and 470 are drawings of typical crystals. The pseudohexagonal character can be seen from Figure 471. Twins with $m\{110\}$ as twin-plane are common. Figure 472 is a contact twin and Fig. 473, a penetration-trilling with slight reëntrant angles.

Cleavage, imperfect parallel to the length of the crystals (010 face). Calcite has perfect cleavage oblique to the length of the crystals.

H. $= 3\frac{1}{2}$. **Sp. gr.** $2.9\pm$.

Color, colorless, white, or amber; also other pale tints. Luster, vitreous; faint resinous on fracture.

Optical Properties. $n_\gamma = (1.68) - n_\alpha\,(1.53) = 0.15$. Double refraction very strong. Fragments are prismatic with parallel extinction, negative elongation, and very high-order interference colors. With dilute H_2SO_4, the hydrochloric acid solution gives the microchemical gypsum test.

Chemical Composition. Calcium carbonate, $CaCO_3$; (CaO = 56.0 per cent.). It often contains a small amount of $SrCO_3$.

Blowpipe Tests. Infusible, but becomes opaque and falls to pieces when heated.

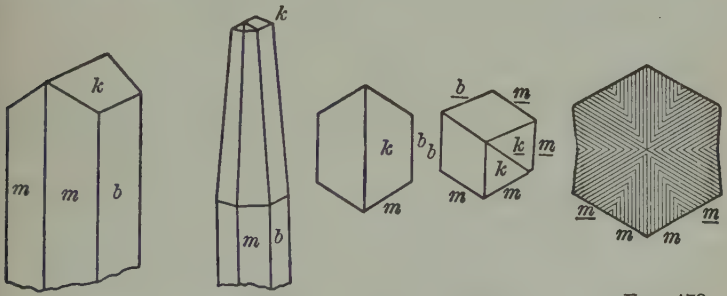


Fig. 469. Fig. 470. Fig. 471. Fig. 472. Fig. 473.

Figs. 469–473.—Aragonite crystals.

Soluble in cold dilute acids with effervescence. In a concentrated solution, dilute H_2SO_4 gives a crystalline precipitate of $CaSO_4 \cdot 2H_2O$. Finely powdered aragonite heated in a test-tube with cobalt nitrate solution becomes lilac colored, while calcite is practically unchanged.

Distinguishing Features. Aragonite and calcite are distinguished by differences in crystal form, cleavage, and specific gravity and if these fail, by the cobalt nitrate test.

Occurrence. 1. As a secondary mineral in basic igneous rocks such as basalt.

2. As a secondary mineral in seams and cavities of limestones along with calcite.

3. In clays and marls along with gypsum. Prominent localities are Girgenti in Sicily and the Pyrenees.

4. As a hot-spring deposit. Carlsbad, Bohemia. This recalls the fact that aragonite often forms as a crust in a tea-kettle.

5. As a mother-of-pearl layer of mollusc shells.

6. As a secondary mineral in serpentine, produced by the decomposition of the pyroxene of the original peridotite.

Strontianite, $SrCO_3$

Form. Strontianite occurs in acicular crystals and also in columnar and fibrous masses. The crystals are pseudohexagonal orthorhombic and resemble those of aragonite.

H. = 3½ to 4. **Sp. gr.** 3.7±.

Color, colorless, white, or pale tints.

Optical Properties. $n_\gamma(1.67) - n_\alpha(1.52) = 0.15$. Like those of aragonite, but gives faint test, if any, for microchemical gypsum.

Chemical Composition. Strontium carbonate, $SrCO_3$; (SrO = 70.1 per cent.). It usually contains some $CaCO_3$, which may be detected by the microchemical gypsum test.

Blowpipe Tests. Infusible, but swells up and gives a crimson flame when heated after it is moistened with HCl.

Soluble in HCl with effervescence. In dilute solutions, H_2SO_4 gives a finely divided white precipitate which distinguishes strontianite from aragonite.

Distinguishing Features. The fibrous or columnar structure and high specific gravity are characteristic. It may be mistaken for celestite, which has about the same specific gravity, but the solubility in HCl will differentiate them.

Uses. The strontium hydroxid used in sugar refining is made from strontianite.

Occurrence. 1. As a secondary mineral produced from celestite.

2. In veins in calcareous marl. Hamm in Westphalia, Germany, is a prominent locality.

Witherite, $BaCO_3$

Form. Witherite occurs in granular or columnar masses in crystalline druses, and in distinct crystals. The crystals are pseudohexagonal twins of pyramidal habit, often resembling quartz crystals. (See Fig. 474.)

H. = 3½. **Sp. gr.** 4.3±.

Color, white or gray. Luster, faint resinous or vitreous.

Optical Properties. $n_\gamma(1.67) - n_\alpha(1.52) = 0.15$. The optical properties are like those of aragonite.

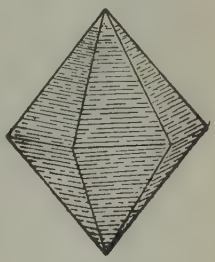


Fig. 474.

Chemical Composition. Barium carbonate, $BaCO_3$; (BaO = 77.7 per cent.).

Blowpipe Tests. Easily fusible, giving a yellowish-green flame.

Soluble in HCl with effervescence. In dilute solution, H_2SO_4 gives a finely divided white precipitate.

Distinguishing Features. The high specific gravity and effervescence in acids distinguish witherite from other minerals.

Occurrence. 1. In veins with galena. Barite is a secondary mineral. The North of England is the only prominent locality for witherite.

CERUSSITE, $PbCO_3$

Form. Cerussite occurs in fibrous and reticulated forms, in compact masses, and also in crystals which are orthorhombic and pseudo-hexagonal. The habit is usually tabular parallel to the side pinacoid $b\{010\}$ (Fig. 476), or pyramidal with $p\{111\}$ and $i\{021\}$ in about equal development (Fig. 475). Other prominent forms are: $m\{110\}$, $a\{100\}$, $r\{130\}$, $k\{011\}$.

Twinning ($m\{100\}$ as twin-plane) is common both as simple contact twins like Fig. 477 and as interpenetrant twins like Fig. 478.

H. = 3½. **Sp. gr.** 6.5±.

Color, colorless, white, gray, and other tints. Luster, adamantine. Very brittle.

Optical Properties. $n_\gamma(2.07)$–$n_\alpha(1.80) = 0.27$. Double refraction very strong. Fragments are mostly irregular with very high-order interference colors, and index of refraction greater than methylene iodid. A nitric acid solution gives octahedral crystals of lead nitrate.

Chemical Composition. Lead carbonate, $PbCO_3$, PbO = 83.5 (Pb = 77.5 per cent.).

Blowpipe Tests. Fuses easily on charcoal. In the closed tube it decrepitates and becomes yellow. Heated on charcoal in R.F., cerussite gives a metallic button and a yellow coating (PbO).

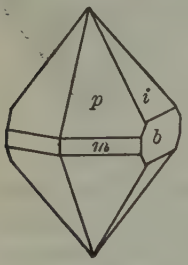


Fig. 475.

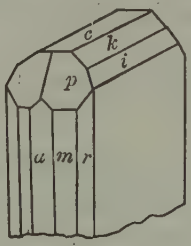


Fig. 476.

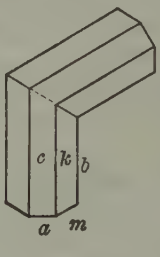


Fig. 477.

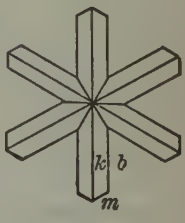


Fig. 478.

Soluble in HNO_3 with effervescence. Soluble in hot HCl, but on cooling needle crystals of adamantine luster ($PbCl_2$) separate.

Distinguishing Features. Distinguished from most other minerals by adamantine luster and high specific gravity. It may usually be distinguished from anglesite by the presence of twinned crystals, but chemical tests may be necessary.

Uses. Cerussite is an ore of lead and sometimes is argentiferous.

Occurrence. 1. Usually derived from galena and occurring especially in the gossan of ore-deposits. Prominent localities are Broken Hill, New South Wales, and Coeur d'Alene district, Idaho. In the Joplin district cerussite pseudomorphs after galena are found.

MALACHITE, $Cu_2(OH)_2CO_3$

Form. For malachite the characteristic recurrences are mammillary crusts, fibrous masses, and acicular crystals. The crystals are monoclinic, but are usually very small and indistinct.

H. = 3½ to 4 **Sp. gr.** 3.9±.

Color, emerald green.

Optical Properties. $n_\gamma(1.91) - n_\alpha(1.66) = 0.25$. Fragments are prismatic with oblique extinction (23°). Interference colors are masked by the green color of the mineral. Arrow-head twins like those of gypsum (Fig. 238) are common among the fragments.

Chemical Composition. Basic copper carbonate, $Cu_2(OH)CO_3$ or $CuCO_3 \cdot Cu(OH)_2$; (Cu = 57.4 per cent.; H_2O = 8.1 per cent.).

Blowpipe Tests. Easily fusible at (3) giving a green flame which is made blue by HCl. In the closed tube it turns black and gives off water.

Soluble in acids with effervescence and gives a green solution.

Distinguishing Features. It is distinguished from other copper minerals of green color by its effervescence in acids. Chrysocolla is blue-green and lacks the fibrous structure of malachite.

Uses. Malachite is sometimes an ore of copper together with azurite, cuprite, and chrysocolla, which are collectively called oxidized ores. Polished malachite with a concentric fibrous structure is used as an ornamental stone.

Occurrence. 1. A characteristic mineral of the upper oxidized zone of copper deposits. It constitutes the so-called "copper-stain," found in outcrops. Malachite is often associated with azurite and is sometimes pseudomorphous after it. Bisbee, Arizona, is a prominent locality.

Azurite, $Cu_3(OH)_2(CO_3)_2$

Form. Azurite occurs in crystals in crystalline coatings and nodular groups of crystals. Crystals are monoclinic, prismatic class, and are usually short prismatic or tabular in habit, often

highly modified. The best specimens come from Chessy in France, hence chessylite, the French name for azurite.

H. = 4. **Sp. gr.** 3.8±.

Color, deep azure blue.

Optical Properties. $n > 1.83$. Fragments are irregular, blue in color, but not pleochroic. Interference colors are masked.

Chemical Composition. Basic copper carbonate, $Cu_3(OH)_2(CO_3)_2$ or $2CuCO_3 \cdot Cu(OH)_2$; (Cu = 55.2 per cent., H_2O = 5.2 per cent.).

Blowpipe Tests. The same as for malachite.

Distinguishing Features. The dark azure blue color is distinctive. It differs from malachite not only in color, but also in water content.

Uses. Azurite is one of the so-called oxidized copper ores.

Occurrence. A characteristic mineral of the oxidized zone. It is usually associated with malachite and has been formed after the malachite. Bisbee, Arizona, has furnished fine specimens of azurite.

Hydromagnesite, $Mg_4(OH)_2(CO_3)_3 \cdot 3H_2O$

Form. Hydromagnesite occurs in crystalline crusts, thin seams, and earthy, chalk-like masses. Crystals, which are very small, are usually like Fig. 479 and are monoclinic and usually twinned on {100}.

H. = 1 to 3. **Sp. gr.** 2.1±.

Color, white. Luster, often pearly.

Optical Properties. $n_\gamma(1.545) - n_\alpha(1.523) = 0.022$. Fragments and crystals are prismatic with parallel extinction, negative elongation, and low-order interference colors.

Chemical Composition. Hydrous basic magnesium carbonate, $Mg_4(OH)_2(CO_3)_3 \cdot 3H_2O$ or $3MgCO_3 \cdot Mg(OH)_2 \cdot 3H_2O$; ($H_2O$ = 19.8 per cent.).

Blowpipe Tests. Infusible. In the closed tube it gives water. Soluble in HCl with effervescence.

Distinguishing Features. Hydromagnesite is distinguished from magnesite by its inferior hardness and abundant water.

Occurrence. 1. As a secondary mineral in serpentine. Alameda county, California (Fig. 479).

FIG. 479.

2. In crystalline limestones, formed directly from brucite, which in turn was formed from periclase (MgO). Crestmore, Riverside county, California.

3. In spring deposits. Atlin, British Columbia.

9. PHOSPHATES, NITRATES, BORATES, ETC.

	Ilmenite,	$FeTiO_3$
	Columbite,	$(Fe,Mn)(Nb,Ta)_2O_6$
Apatite Group	APATITE,	$Ca_{10}F_2(PO_4)_6$
	Dahllite,	$Ca_{10}(CO_3)(PO_4)_6$
	Pyromorphite,	$Pb_{10}Cl_2(PO_4)_6$
	Mimetite,	$Pb_{10}Cl_2(AsO_4)_6$
	Vanadinite,	$Pb_{10}Cl_2(VO_4)_6$
	COLLOPHANE,	$3Ca_3(PO_4)_2 \cdot Ca(CO_3,F_2)(H_2O)_x$
	Turquois,	$H_5[Al(OH)_2]_6 \cdot Cu(OH)(PO_4)_4$
	Carnotite,	$K_2(UO_2)_2(VO_4)_2 \cdot 8H_2O$
	Nitratine,	$NaNO_3$
	Colemanite,	$Ca_2B_6O_{11} \cdot 5H_2O$
	Ulexite,	$NaCaB_5O_9 \cdot 8H_2O$
	Pitchblende,	$(UO_2)_2UO_4 \cdot (H_2O)_x$

About 150 phosphate minerals are known but most of them are rare. Basic phosphates of iron and of copper are especially numerous. The compounds are practically all orthophosphates, that is, salts of H_3PO_4.

Ilmenite and columbite properly belong to other divisions, but are placed here for convenience.

Of the few mineral nitrates known, nitratine (sodium nitrate) is the only one of importance. Only a few borates are prominent as minerals. H_3BO_3 is boric acid. Borax is a salt of $H_2B_4O_7$, which is derived thus: $4H_3BO_3 - 5H_2O = H_2B_4O_7$. Colemanite is a salt of $H_4B_6O_{11}$ $(6H_3BO_3 - 7H_2O)$. These are called tetra- and hexa-boric acids respectively.

Ilmenite, $FeTiO_3$

Form. Ilmenite occurs in tabular hexagonal crystals, in flat plates without definite outline, in disseminated grains, in com-

pact masses, and in the form of sand. The crystals resemble those of hematite in habit and angles, but the crystal class is different, for ilmenite belongs to the rhombohedral class.

H. = 5 to 6. **Sp. gr.** 4.7±.

Color, black. Luster, submetallic to metallic. Streak, black to brownish-red. Slightly magnetic.

Chemical Composition. Ferrous metatitanate, $FeTiO_3$; (FeO = 47.3 per cent.), analogous to a metasilicate. Ilmenite usually contains ferric iron and also magnesium. It grades on the one hand into hematite and on the other into $MgTiO_3$ (geikielite).

Analyses of the Minerals of the Ilmenite Group

	FeO	MgO	MnO	TiO_2	Fe_2O_3
Ilmenite	22.4	0.5	0.3	23.7	53.7
Ilmenite	36.5	0.6	2.7	45.9	14.3
Ilmenite (Picroilmenite)	24.4	14.2	....	56.1	5.4
Geikielite	6.3	28.5	....	63.8	1.9

Blowpipe Tests. Infusible. The sodium carbonate fusion dissolved in HCl and boiled with metallic tin gives a violet solution.

Slowly soluble in HCl. Decomposed by fusion with $KHSO_4$.

Distinguishing Features. Ilmenite may be mistaken for hematite or magnetite. It fails to give the red streak of the former and the strong magnetism of the latter. When it is intimately mixed with hematite and magnetite, polished surfaces are necessary to identify it.

Occurrence. 1. As an accessory constituent of igneous rocks, especially diabases.

2. As a magmatic segregation in igneous rocks intergrown with magnetite and forming the so-called titaniferous magnetites.

3. As a prominent constituent of sands, especially the "black sands."

Columbite, $(Fe,Mn)(Nb,Ta)_2O_6$

Form. Columbite usually occurs in orthorhombic crystals of short prismatic or tabular habit.

Cleavage, fair in two directions at right angles.

H. = 6. **Sp. gr.** 5.5–6.5.

Color, black, often iridescent. Luster, submetallic.

Chemical Composition. An iron and manganese meta-niobate and meta-tantalate grading from $(Fe,Mn)Nb_2O_6$ to $(Fe,Mn)Ta_2O_6$. The latter mineral is called tantalite.

Blowpipe Tests. Fusible on the edges with difficulty ($5\frac{1}{2}$). On charcoal with sodium carbonate in R.F. it gives a magnetic residue. The sodium carbonate bead in O.F. is opaque bluish-green (Mn.). The borax fusion dissolved in HCl with tin gives a deep blue color.

Distinguishing Features. Columbite resembles wolframite and gives almost identical blowpipe tests, but the latter has higher specific gravity and more perfect cleavage.

Insoluble in acids.

Uses. Tantalum, which is used as a filament for incandescent lights, is obtained from columbite and tantalite.

Occurrence. 1. In granite pegmatites, associated with beryl, lepidolite, spodumene, etc. The Etta mine in the Black Hills, South Dakota, is the most prominent locality in the United States.

APATITE GROUP—HEXAGONAL

The apatite group is a well-established isomorphous group of minerals, for several isomorphous mixtures are known as given in the analyses below. Besides fluor-apatite $3Ca_3(PO_4)_2 \cdot CaF_2$ and chlor-apatite, $3Ca_3(PO_4)_2 \cdot CaCl_2$, there are dahllite, $3Ca_3(PO_4)_2 \cdot CaCO_3$, voelckerite, $3Ca_3(PO_4)_2 \cdot CaO$, and a rare mineral called svabite, $3Ca(AsO_4)_2 \cdot CaF_2$. The following are typical analyses of the minerals of this group (given in the form of metals and acid radicals instead of the usual form).

Analyses of Minerals of the Apatite Group

	Ca	Pb	PO_4	AsO_4	VO_4	Cl	F	Misc.
Fluor-apatite, Portland	39.5	....	55.4	....	....	0.2	3.8	1.1
Chlor-apatite, Norway	37.2	....	54.2	....	....	5.0	...	3.1
Voelckerite, Zillerthal	40.4	....	57.5	....	....	...	0.6	O = 1.4, H_2O = 0.1
Dahllite (Podolite), Russia	36.5	....	52.2	....	....	...	...	CO_3 = 5.3, Fe_2O_3 = 3.0
Pyromorphite, Freiberg	4.6	67.0	26.0	0.8	....	1.9	...	
Pyromorphite, Schemnitz	0.2	75.1	21.3	....	....	2.5	...	
Pyromorphite, Roughten Gill	....	71.7	15.1	10.9	....	2.3	...	1.7
Mimetite, Bohemia	....	70.6	0.8	26.7	....	2.5	...	
Endlichite, New Mexico	0.2	68.2	tr	16.1	13.7	2.5	...	
Vanadinite, Arizona	....	71.7	1.9	....	24.7	2.4	...	
Svabite, Jakobsberg	30.1	2.8	0.5	61.7	....	0.1	2.0	2.6

APATITE, $Ca_{10}F_2(PO_4)_6$

Form. Apatite is found in crystals and in massive forms. The crystals are hexagonal and belong to the bipyramidal class

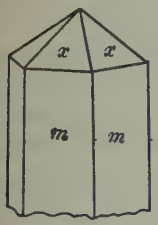


Fig. 480.

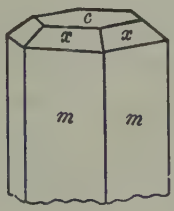


Fig. 481.

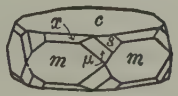


Fig. 482.

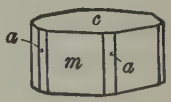


Fig. 483.

as there is but one plane of symmetry which is horizontal. The habit is usually prismatic with the following forms: $m\{10\bar{1}0\}$, $c\{0001\}$, and $x\{10\bar{1}1\}$. Interfacial angles: $mx(10\bar{1}0:10\bar{1}1) = 49°\ 42'$; $xx(10\bar{1}1:01\bar{1}1) = 37°\ 44\frac{1}{2}'$. Figures 480 to 483 represent usual types of crystals. In Fig. 482, the general form $\mu\{21\bar{3}1\}$ is present in addition to $s\{11\bar{2}1\}$ and other forms.

Cleavage, imperfect basal parallel to $\{0001\}$.

H. = 5. **Sp. gr.** 3.2±.

Color, usually reddish-brown or green, more rarely white, colorless, gray, or violet. Luster, subresinous.

Optical Properties. $n_\gamma(1.646) - n_\alpha(1.641) = 0.005$. Fragments are irregular, and colorless with low first-order interference colors. It gives the microchemical gypsum test with dilute H_2SO_4.

Chemical Composition. Apatite is an isomorphous mixture of the tricalcium fluophosphate, $Ca_{10}F_2(PO_4)_6$ with smaller amounts of $Ca_{10}Cl_2(PO_4)_6$, $Ca_{10}O(PO_4)_6$, and $Ca_{10}(CO_3)(PO_4)_6$. For $Ca_{10}F_2(PO_4)_6$ (Ca = 39.7 per cent., F = 3.8 per cent., PO_4 = 56.5 per cent.). Some varieties contain manganese.

Blowpipe Tests. Fusible on edges (5½) and gives a yellowish-red flame which is made green with H_2SO_4.

Soluble in HNO_3, sometimes with slight effervescence on heating. The solution gives a yellow precipitate with an excess of $(NH_4)_2MoO_4$ solution when warmed. As NH_4OH gives a white precipitate of calcium phosphate, the best test for calcium is dilute H_2SO_4 which in the presence of 50 per cent. alcohol gives a crystalline precipitate of $CaSO_4 \cdot 2H_2O$.

Distinguishing Features. Apatite is distinguished from most similar minerals by its crystal form, hardness (just less than a knife blade), and subresinous luster. Collophane is amorphous, has lower specific gravity, and effervesces in acids.

Uses. Massive apatite is used to some extent in the preparation of superphosphate for fertilizer, but most of the superphosphate is made from so-called phosphate rock which is largely collophane.

Occurrence. 1. As an accessory constituent of igneous rocks, very common and widely distributed but in small quantities. It is the original source of the phosphates of sedimentary rocks.

2. In high-temperature veins with phlogopite, calcite, and diopside.

3. In metamorphic rocks.

4. In granite pegmatites.

Dahllite, $Ca_{10}(CO_3)(PO_4)_6$

Form. Dahllite occurs in colloform fibrous incrustations on collophane, rarely in minute hexagonal crystals.

H. = 5. **Sp. Gr.** = 3.0±.

Color, white or pale tints.

Optical Properties. $n_\gamma(1.623) - n_\alpha(1.619) = .004$. Fragments are prismatic to acicular with parallel extinction, negative elongation, and low to middle first order interference colors.

Chemical Composition. Calcium carbonate-phosphate, $Ca_{10}(CO_3)(PO_4)_6$, analogous to fluor-apatite. (Ca = 38.9 per cent. PO_4 = 55.3, CO_3 = 5.8.) Water is usually present, but it is probably mechanically held as in chalcedony.

Blowpipe Tests. Fusible with difficulty, but usually decrepitates. In the closed tube it gives a small amount of water.

Soluble in cold dilute HNO_3 with slight effervescence; effervesces vigorously in hot HNO_3. The solution gives tests for calcium with dilute H_2SO_4 and alcohol, and for PO_4 with ammonium molybdate.

Distinguishing Features. Dahllite is distinguished from collophane by its crystalline character and small water content, and from apatite by its effervescence in HNO_3.

Uses. Some dahllite occurs in phosphorites (the hard rock phosphate of Florida, for example) along with collophane and is used for superphosphate.

Occurrence. 1. In phosphorite or so-called phosphate rock as an incrustation on collophane. Marion county, Florida.

Pyromorphite, $Pb_{10}Cl_2(PO_4)_6$

Form. Pyromorphite usually occurs as small crystals and earthy crusts. The crystals are hexagonal and prismatic in habit; $c\{0001\}$ and $m\{10\bar{1}0\}$ are the only common forms (Fig. 484).

H. = 3½ to 4. **Sp. gr.** 6.8±.

Color, green or brown. Luster, adamantine.

Optical Properties. $n_\gamma(2.061) - n_\alpha(2.049) = 0.012$. Fragments are irregular, colorless or pale green, and have low first-order interference colors. With HNO_3 isometric crystals of lead nitrate are deposited.

Chemical Composition. Lead chlorid-phosphate, $Pb_{10}Cl_2(PO_2)_4$; (Pb = 76.3 per cent.). In some varieties Ca replaces Pb (p. 313), and in others (VO_4) replaces (PO_4).

Blowpipe Tests. Easily fusible (at 2) on charcoal to a globule with apparent crystal faces. With sodium carbonate on charcoal it yields a lead button. With a $NaPO_3$ bead saturated with CuO it gives an azure-blue flame (Cl).

FIG. 484.

Soluble in HNO_3. An excess of $(NH_4)_2\ MoO_4$ gives a yellow ppt. with the nitric acid solution.

Distinguishing Features Pyromorphite is distinguished from other minerals with adamantine luster by its hexagonal form.

Occurrence. 1. As a secondary mineral formed from galena. Phoenixville, Pennsylvania, is a prominent locality. Both pyromorphite pseudomorphs after galena and galena pseudomorphs after pyromorphite have been noted, the former from the Joplin district and the latter from Huelgoat, France.

Mimetite, $Pb_{10}Cl_2(AsO_4)_6$

Form. Mimetite usually occurs in rounded hexagonal crystals.

H. = 3½. **Sp. gr.** 7.2±.

Color, yellow, orange, or red. Luster adamantine.

Optical Properties. $n_\gamma(2.13) - n_\alpha(2.12) = 0.01$. Fragments are irregular yellow, and have low first-order interference colors. With HNO_3 isometric crystals of $Pb(NO_3)_2$ are deposited.

Chemical Composition. Lead chlorid-arsenate, $Pb_{10}Cl_2(AsO_4)_6$; (Pb = 69.5 per cent.). It grades on the one hand into pyromorphite and on the other into vanadinite.

Blowpipe Tests. Easily fusible (at 1½) on charcoal and gives

a white sublimate and a metallic button. In the closed tube heated with charcoal it gives an arsenic mirror test for an arsenate. With CuO in $NaPO_3$ bead it gives an azure-blue flame (Cl).

Soluble in HNO_3. With $(NH_4)_2MoO_4$ the nitric acid solution gives a yellow precipitate on boiling (phosphates give the precipitate on slight warming). In order to determine the presence of the phosphate radical it is necessary to remove the arsenic by means of H_2S.

Distinguishing Features. Mimetite is difficult to distinguish at sight. The adamantine luster and high specific gravity suggest that it is a lead mineral.

Occurrence. 1. As a secondary mineral in lead mines. Cumberland, England.

Vanadinite $Pb_{10}Cl_2(VO_4)_6$

Form. Vanadinite practically always occurs in small hexagonal crystals of prismatic habit. The common forms are: $c\{0001\}$ and $m\{10\bar{1}0\}$ (Fig. 485). The general form $\{21\bar{3}1\}$, a hexagonal bipyramid, is sometimes present.

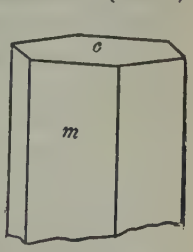


FIG. 485.—Vanadinite.

H. = 3. **Sp. gr.** 6.8±.

Color, usually red, but also yellow and brown. Luster, adamantine.

Optical Properties. $n_\gamma(2.35) - n_\alpha(2.30) = 0.05$. Fragments are irregular yellow or orange color, and give bright interference colors.

Chemical Composition. Lead chlorid-vanadate, $Pb_{10}Cl_2(VO_4)_6$; (Pb = 72.7 per cent.). It often contains (PO_4) and (AsO_4) as replacing radicals. Endlichite is intermediate between vanadinite and mimetite (see analyses, page 313).

Blowpipe Tests. Easily fusible (at 1½) on charcoal, giving a white sublimate and a metallic globule. In the closed tube with $KHSO_4$ it gives a yellow mass. The $NaPO_3$ bead is green in R.F. and yellow in O.F. It gives the Cl test with a $NaPO_3$ bead saturated with CuO.

Soluble in HNO_3.

Uses. Vanadinite is one source of the vanadium used as alloy with steel and of various compounds used in dyeing and the manufacture of ink.

Distinguishing Features. Vanadinite is distinguished from most minerals by the adamantine luster and hexagonal crystals. It is distinguished from pyromorphite by its color.

Occurrence. 1. A secondary mineral formed from galena and often associated with wulfenite. Yuma county, Arizona, is a prominent locality.

Vivianite, $Fe_3(PO_4)_2.8H_2O$

Form. Vivianite occurs in small crystals, in nodules, and in earthy masses. Crystals are monoclinic with varying habit.

Cleavage, perfect in one direction (010).

H. = 2. **Sp. gr.** 2.6±.

Color, deep blue or bluish-green, but colorless if unaltered.

Optical Properties. $n_\gamma(1.62) - n_\alpha(1.57) = 0.05$. Fragments are prismatic with either parallel or oblique ($28\frac{1}{2}°$) extinction. Pleochroic from blue to colorless or blue to green.

Chemical Composition. Hydrous ferrous phosphate, $Fe_3(PO_4)_2 \cdot 8H_2O$; (H_2O = 28.7 per cent.). It usually contains some ferric iron as the result of oxidation.

Blowpipe Tests. Easily fusible (2) to a black magnetic globule. In the closed tube gives water and whitens. It gives the borax bead test for ferrous iron. (A bead made blue with CuO becomes opaque red in a neutral flame.)

Soluble in HNO_3 or HCl. $(NH_4)_2MoO_4$ gives a yellow ppt.

Distinguishing Features. The dark blue color and inferior hardness are distinctive.

Occurrence. 1. As a secondary mineral in veins associated with pyrite and pyrrhotite. Ibex mine, Leadville, Colorado.

2. In clay and marl beds sometimes replacing fossils and in soils often around the roots of trees. At Mullica Hill, New Jersey, it replaces fossil belemnites.

COLLOPHANE, $3Ca_3(PO_4)_2 \cdot Ca(CO_3,F_2)(H_2O)_x$

Form. Amorphous. Usually massive, often concretionary or oölitic and sometimes banded. It is often a replacement of bone. Colloform crusts may be present in open spaces.

H. = 3 to 5. **Sp. gr.** 2.6—2.9 (variations are dependent upon purity and porosity.

Color, white, yellow, brown, gray, or black (coloration is due to an organic pigment).

Optical Properties. $n = 1.58-1.62$. Fragments are irregular, colorless to brown, translucent, with high relief in clove oil and low relief in cinnamon oil. Between crossed nicols the mineral is either dark or has low first-order interference colors (the double refraction is due to strain).

Chemical Composition. Hydrous calcium carbonophosphate often containing fluorin, approaching the formula $3Ca_3(PO_4)_2 \cdot Ca(CO_3,F_2)(H_2O)_x$. Organic matter, aluminum, and iron are usually present, and sometimes the sulfate radical. Calcite is the principal mechanical impurity.

The following analysis give some ideas of the purer forms of collophane.

Analyses of Collophane

	Ca	Al	Fe	Mg	PO_4	CO_3	SO_4	F	H_2O	Misc.
Sombrero.....	36.2	...	...	0.6	52.3	5.4	...	...	5.0	...
Pouzillac.....	35.5	0.1	0.3	...	50.0	5.1	...	0.9	7.1	0.3
Mouillac.....	37.0	...	...	...	50.3	5.5	...	1.5	4.8	...
Nauru.....	34.7	0.5	0.3	1.2	48.8	2.5	...	...	7.2	0.1

Blowpipe Tests. Fuses (at 5 to 6) with difficulty on the edges, glows, and turns white. In the closed tube it turns dark and gives water (1 to 8 per cent.).

It is soluble in cold dilute nitric acid with slight to moderate effervescence; when the acid is heated there is vigorous effervescence. A *hot* nitric solution gives a yellow precipitate with

an excess of ammonium molybdate solution. The solution gives the calcium test with dilute H_2SO_4 and 50 per cent. alcohol (see p. 39 for separation of calcium, etc.).

Distinguishing Features. Collophane is a difficult mineral to recognize without chemical and optical tests on account of its variable appearance. A mineral showing bone structure is almost certain to be collophane. It is distinguished from opal and chalcedony by inferior hardness, from calcite by its greater hardness and optical tests, from apatite by its amorphous nature, decided effervescence in acids, and optical tests. It is apt to be overlooked because of its indefinite character.

Uses. Phosphorite or so-called phosphate rock, the chief constituent of which is collophane, is used in the manufacture of superphosphate, a valuable fertilizer made by treating the crude material with sulfuric acid. The United States and Tunis are the largest producers. The states in order of production are Florida, Tennessee, and South Carolina. Large deposits occur in southeastern Idaho and adjoining portions of Utah and Wyoming and extend into Montana.

Occurrence. 1. In bedded deposits, often formed by the replacement of limestones. Marion county, Florida.

2. In recent deposits. Nauru Island, Pacific Ocean.

3. As a replacement of fossil bones. The bone structure is retained and cavities are often filled with calcite or chalcedony. The organic matter has largely disappeared, but some of it remains as a pigment.

Turquois, $H_5[Al(OH)_2]_6Cu(OH)(PO_4)_4$

Form. Turquois occurs in seams and incrustations, and is apparently amorphous, but the polarizing microscope proves it to be crystalline and at one locality it has been found in minute triclinic crystals.

H. = 6. **Sp. gr.** 2.7±.

Color, usually bluish-green but varies from blue to green.

Optical Properties. $n_\gamma(1.65) - n_\alpha(1.61) = .04$. Fragments

are irregular, bluish or greenish with aggregate polarization in low first-order interference colors.

Chemical Composition. Acid and basic aluminum copper phosphate, probably $H_5[Al(OH_2)]_6 \cdot Cu(OH)(PO_4)_4$, ($H_2O$ = 19.5 per cent).

Blowpipe Tests. Infusible, but turns dark when heated and gives a green flame which is made blue by HCl. In the closed tube at a high temperature it gives water and turns dark.

Soluble in HCl.

Distinguishing Features. The only common mineral resembling turquois is chrysocolla from which it is distinguished by superior hardness. The association of chrysocolla with other copper minerals is also an aid in its identification.

Uses. Turquois is used extensively as a gem. Blue stones are more valuable than green ones.

Occurrence. 1. In seams of volcanic rocks such as trachytes and rhyolites. Los Cerrillos Mts., New Mexico (in andesite).

Carnotite, $K(UO_2)_2(VO_4)_2 \cdot 8H_2O$

Form. An apparently amorphous mineral occurring in earthy masses, impregnations, or as incrustations. Carnotite, however, is crystalline and minute tabular orthorhombic crystals have been described.

H. = rather soft. **Sp. gr.** = 4.1 ±.

Color, canary yellow.

Optical Properties. $n_\gamma(1.95) - n_\alpha(1.75) = 0.20$. Fragments are yellow and doubly-refracting.

Chemical Composition. Hydrous potassium uranyl vanadate, $K_2(UO_2)_2(VO_4)_2 \cdot 8H_2O$ (H_2O = 14.5 per cent.). Calcium replaces part of the potassium. The corresponding calcium mineral is called tyuyamunite.

Blowpipe Tests. Fusible (at 2½) to a black non-magnetic slag. It gives a yellow $NaPO_3$ bead in O.F. which becomes a fine green in the R.F. In the closed tube it darkens and gives water.

Soluble in cold dilute acids.

Distinguishing Features. Carnotite is easily recognized by its bright canary yellow color.

Uses. Carnotite is used for the production of vanadium, uranium, and radium salts.

Occurrence. 1. As an incrustation or impregnation in sandstones, sometimes associated with fossil wood. It is evidently a secondary mineral derived from some pre-existing minerals. Western Colorado and eastern Utah.

Nitratine, $NaNO_3$

Form. Nitratine or "soda niter" is found in crystalline and granular masses. It crystallizes in rhombohedrons with almost the same angles as the unit or cleavage rhombohedron of calcite ($10\bar{1}1 : 01\bar{1}1 = 73° 30'$).

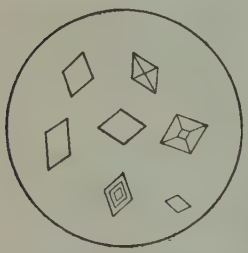


Fig. 486.—Nitratine recrystallized.

Cleavage, rhombohedral like calcite.

H. = 1½ to 2. **Sp. gr.** 2.3±.

Color, white or colorless. Very deliquescent.

Optical Properties. $n_\gamma(1.587) - n_\alpha(1.336) = 0.251$. It recrystallizes from water solution in rhombic shaped crystals (Fig. 486) with symmetrical extinction and very high-order interference colors which greatly resemble calcite cleavage fragments. The indices of refraction, however, are much lower than those of calcite.

Chemical Composition. Sodium nitrate, $NaNO_3$. Iodin may be present in the form of $Ca(IO_3)_2$, which imparts a yellow tint.

Blowpipe Tests. Easily fusible (at 1), giving an intense yellow flame. With $KHSO_4$ in the closed tube it gives red-brown fumes of NO_2.

Soluble in water.

Distinguishing Features. Nitratine is distinguished by its cooling, saline taste, and by the optical tests which are much like those of calcite.

Uses. Nitratine is used as a fertilizer and also in the manufacture of potassium nitrate. Chile furnishes the world's supply.

Occurrence. 1. In superficial beds ("caliche") in arid regions. Occurs in northern Chile and to a slight extent in California and Nevada.

2. In caves. Holmdale, Idaho.

Colemanite, $Ca_2B_6O_{11}\cdot 5H_2O$

Form. Colemanite occurs in crystals, which often line geodes, and in crystalline and compact masses. The crystals are monoclinic and are often highly modified.

Cleavage, perfect in one direction parallel to (010).

H. = 4½. **Sp. gr.** 2.4±.

Color, colorless or white.

Optical Properties. $n_\gamma(1.61) - n_\alpha(1.58) = 0.03$. Fragments are irregular plates with bright interference colors. Pseudo-hexagonal crystals of boric acid separate from the hydrochloric acid solution (Fig. 487).

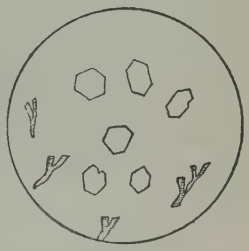


Fig. 487.—Boric acid.

Chemical Composition. Hydrous calcium hexa-borate, $Ca_2B_6O_{11}\cdot 5H_2O$; (B_2O_3 = 50.9 per cent., H_2O = 21.9 per cent.).

Blowpipe Tests. Fuses easily (at 1½) with exfoliation, coloring the flame green. In the closed tube it gives water.

Soluble in hot HCl. Boric acid separates out on cooling.

Distinguishing Features. Colemanite is distinguished from most minerals by its perfect cleavage in one direction. From gypsum it is distinguished by its greater hardness.

Uses. Colemanite is the principal source of borax and boric acid. It is obtained in San Bernardino, Inyo, and Los Angeles counties, California.

Occurrence. 1. In shales and probably formed by the replacement of ulexite. Calico, San Bernardino county, California.

Ulexite, $NaCaB_5O_9 \cdot 8H_2O$

Form. Ulexite is found in rounded fibrous masses, locally called "cotton-balls," and also in compact translucent masses.

H. = 1 – 3. **Sp. gr.** 1.6 ±.

Color, white. Luster, silky to *vitreous*.

Optical Properties. $n_\gamma(1.520) - n_\alpha(1.500) = .020$. Fragments are acicular with parallel extinction, negative elongation, and low first-order interference colors.

Chemical Composition. Hydrous sodium calcium pentaborate, $NaCaB_5O_9 \cdot 8H_2O$; (H_2O = 35.5 per cent.).

Blowpipe Tests. Easily fusible (1) with intumescence, coloring the flame an intense yellow. In closed tube gives water.

Soluble in hot HCl; H_3BO_3 separates out on cooling.

Uses. It is a source of borax in northern Chile.

Distinguishing Features. The soft rounded masses with fibrous structure and silky luster are characteristic.

Occurrence. 1. In playas or the dried-up lakes of arid regions associated with borax, gypsum, and halite. Esmeralda County, Nevada.

Pitchblende, $(UO_2)_2UO_4(H_2O)_x$

Form. Pitchblende is usually massive and sometimes has a colloform surface. It is an amorphous mineral. Uraninite is the crystalline equivalent.

H. = 5½. **Sp. gr.** 6.5 to 8.0.

Color, dark brown to black. Luster, submetallic or pitch-like. Streak usually olive-green.

Optical Properties. $n > 1.74$. Fragments are irregular, translucent brown, and isotropic.

Chemical Composition. Probably uranyl uranate $(UO_2)_2UO_4(H_2O)_x$. Lead and radium are present, the latter in very small quantities.

Blowpipe Tests. Infusible. The $NaPO_3$ bead is yellowish-green in O.F. and green in R.F. It gives water in the closed tube

Soluble in HNO_3. With NH_4OH the solution gives a yellow precipitate.

Distinguishing Features. This mineral has no very distinctive characters outside of its high specific gravity and pitchy luster.

Uses. Uraninite is the source of uranium compounds and also of radium compounds.

Occurrence. 1. In veins with metallic sulfids. Joachimsthal, Bohemia.

10. SULFATES

A. Normal Anhydrous Sulfates

Barite Group	BARITE,	$BaSO_4$
	Celestite,	$SrSO_4$
	Anglesite,	$PbSO_4$
	ANHYDRITE,	$CaSO_4$

B. Basic and Hydrous Sulfates

	Kainite,	$MgSO_4 \cdot KCl \cdot 3H_2O$
	Brochantite,	$Cu_4(OH)_6SO_4$
	GYPSUM,	$CaSO_4 \cdot 2H_2O$
	Chalcanthite,	$CuSO_4 \cdot 5H_2O$
Alunite Group	Alunite,	$KAl_3(OH)_6(SO_4)_2$
	Jarosite,	$KFe_3(OH)_6(SO_4)_2$

A large number of sulfate minerals, most of them basic and hydrous salts, are known, but comparatively few are of much importance. They are all salts of H_2SO_4. No sulfites, pyrosulfates, thiosulfates, or persulfates are known among minerals.

BARITE GROUP—ORTHORHOMBIC

In crystal habit, angles, and cleavage barite, celestite, and anglesite are similar, and thus constitute an isomorphous group. One would expect to find anhydrite in this group, but it differs in angles and especially in cleavage. There are isomorphous mixtures of $BaSO_4$ and $SrSO_4$, also $BaSO_4$ and $PbSO_4$. The following are analyses of minerals of this group.

Analyses of Minerals of the Barite Group

	BaO	SrO	CaO	PbO	SO_3	Misc.
Strontium-bearing barite	43.8	13.9	0.1	....	36.9	3.7
Lead-bearing barite (Hokutolite)	48.9	....	...	17.8	32.2	Ign. = 0.6
Celestite	....	54.7	1.4	....	43.8	
Anglesite	....	....	...	74.0	25.7	H_2O = 0.3

BARITE $BaSO_4$

Form. Barite occurs in crystals, in crested groups, in lamellar, nodular, fibrous, and granular masses.

Rhombic bipyramidal class: $\breve{a}:\bar{b}:\dot{c} = 0.815:1:1.313$. Usual forms: $c\{001\}$, $m\{110\}$, $o\{011\}$, $u\{101\}$, $d\{102\}$, $l\{104\}$, $z\{111\}$, $y\{122\}$. Interfacial angles: mm $(110:1\bar{1}0) = 78° 22'$; co $(001:011) = 52° 43'$; cu $(001:101) = 58° 10\frac{1}{2}'$; cd $(001:102) = 38° 51\frac{1}{2}'$; cl $(001:104) = 21° 56\frac{1}{2}'$; cz $(001:111) = 64° 19'$; oy $(011:122) = 26° 1'$. The habit is usually tabular parallel to $\{001\}$, as represented in Figs. 488 to 491, but prismatic crystals are also common. (See Fig. 203, p. 115).

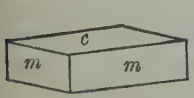


FIG. 488.

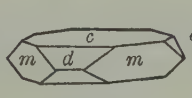


FIG. 489.

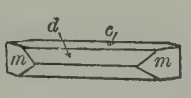


FIG. 490.

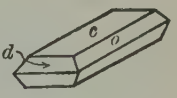


FIG. 491.

FIGS. 488–491.—Barite.

Cleavage, parallel to $c\{001\}$ and to $m\{110\}$. The cleavage form is like Fig. 488, with two right angles and one oblique angle (78° 22′).

H. = 3. **Sp. gr.** 4.5±.

Color, colorless, white, gray and tints of brown, blue, green, etc.

Optical Properties, $n_\gamma(1.647) - n_\alpha(1.636) = 0.011$. Fragments are rhombic with symmetrical extinction or rectangular with parallel extinction. The interference colors are bright.

Chemical Composition. Barium sulfate, $BaSO_4$; (BaO = 65.7 per cent.) Strontium and lead often replace part of the barium.

Blowpipe Tests. Fusible (at 4), coloring the flame yellowish-green. Unaltered in the closed tube, but usually decrepitates. The water solution of the sodium carbonate fusion gives a white precipitate with $BaCl_2$, which is insoluble in HCl. The acetic acid solution of the residue gives a yellow precipitate with K_2CrO_4.

Insoluble in acids.

Distinguishing Features. Barite can usually be recognized by its lamellar structure and high specific gravity.

Uses. Barite is used in the manufacture of paint as a substitute for white lead and also in the manufacture of barium salts.

Occurrence. 1. As a gangue mineral in veins, associated with galena, sphalerite, dolomite, calcite, etc.

2. As lenticular masses in clays overlying limestones. These are residual deposits formed by the weathering of the limestone.

3. As a metasomatic replacement of limestone and in cavities in limestones.

Celestite, $SrSO_4$

Form. Celestite occurs in crystals, in cleavable masses, and in fibrous seams. The crystals are like barite in habit, forms, and angles. Crystals one and a half feet in length have been found on the Island of Put-In-Bay, Lake Erie.

Cleavage, perfect parallel to {001}, and imperfect parallel to {110}.

H. = 3. **Sp. gr.** 3.9±.

Color, colorless, white, pale blue; sometimes red.

Optical Properties. $n_\gamma(1.631) = n_\alpha(1.622) = 0.009$. Fragments are like those of barite.

Chemical Composition. Strontium sulfate, $SrSO_4$; (SrO = 56.4 per cent.). Calcium and barium sometimes are present.

Blowpipe Tests. Fusible (at 4) giving a crimson red flame with HCl. The water solution of the sodium carbonate fusion gives a white ppt. with $BaCl_2$, which is insoluble in HCl. The acetic acid solution of the residue fails to give a precipitate with K_2CrO_4, but the addition of NH_4OH and alcohol causes a yellow ppt. to form.

Insoluble in acids.

Distinguishing Features. Celestite greatly resembles barite but can often be distinguished by its imperfect prismatic cleavage. It is not as heavy as barite.

Uses. Celestite is used to some extent in the manufacture of fire-works.

Occurrence. 1. In cavities in limestone. Near Austin, Texas.

2. In marl with sulfur and gypsum. Girgenti, Sicily.

Anglesite, $PbSO_4$

Form. There are two characteristic occurrences of anglesite: in crystals in cavities, and in masses with a banded structure. The crystals are orthorhombic and of varied habit. See Figs. 492–494, in which $m\{110\}$, $a\{100\}$, $c\{001\}$, $d\{102\}$, $o\{011\}$, $z\{111\}$, $y\{122\}$. The angles are almost the same as for barite. Unlike cerussite it never occurs in twin-crystals.

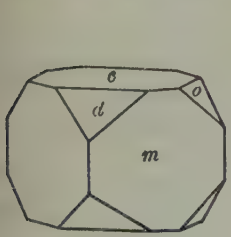


Fig. 492.

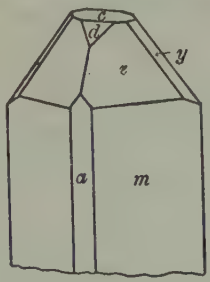


Fig. 493.

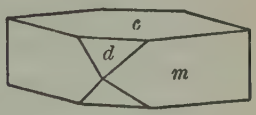


Fig. 494.

Figs. 492–494.—Anglesite.

Cleavage, imperfect and not important.

H. = 3. **Sp. gr.** 6.3±.

Color, colorless, white, or gray. Luster, adamantine to dull.

Optical Properties. $n_\gamma(1.893) - n_\alpha(1.877) = 0.016$. Fragments are irregular with bright interference colors (cerussite has very high-order colors).

Chemical Composition. Lead sulfate, $PbSO_4$; (PbO = 73.6 per cent., Pb = 68.3 per cent.).

Blowpipe Tests. Easily fusible (at 1½) on charcoal to a white globule. In R.F. on charcoal gives a metallic button.

Soluble in HNO_3 with difficulty. Soluble in $NH_4(C_2H_3O_2)$ (made by neutralizing acetic acid with ammonium hydroxid).

Distinguishing Features. In its general appearance and associates, anglesite resembles cerussite from which it is usually distinguished by the similarity of its crystals to those of barite and by the absence of twinned crystals. It also has weaker double refraction than cerussite.

Uses. Anglesite is one of the minor ores of lead.

Occurrence. 1. As a secondary mineral in the oxidized zone of lead mines. It often accompanies cerussite and is sometimes pseudomorphous after galena. It frequently occurs as band surrounding galena and between it and cerussite. Phoenixville, Pennsylvania.

ANHYDRITE, $CaSO_4$

Form. Anhydrite occurs in cleavable and granular masses and but rarely in orthorhombic crystals.

Cleavage, in three directions at right angles (pseudo-cubic).

H. = 3 to 3½. **Sp. gr.** 2.9±.

Color, colorless, white, gray, bluish, or reddish. Luster, pearly on cleavage faces.

Optical Properties. $n_\gamma(1.61) - n_\alpha(1.57) = 0.04$. Fragments are square and rectangular with parallel extinction and bright interference colors. There are often twinning striations parallel to the diagonals of the squares. With dilute HCl, microchemical gypsum is formed (Fig. 4, p. 43).

Chemical Composition. Anhydrous calcium sulfate, $CaSO_4$; (CaO = 41.2 per cent.).

Blowpipe Tests. Fuses (at 3) and colors the flame yellowish-red. In the closed tube it may yield a little water due to partial hydration to gypsum.

Soluble with difficulty in HCl.

Distinguishing Features. Anhydrite is recognized by its pseudo-cubic cleavage and by its moderate specific gravity (heavier than calcite and lighter than barite). It is heavier and harder than gypsum and only soluble with difficulty in HCl.

Occurrence. 1. In bedded deposits due to the direct deposi-

tion of sea-water and often associated with halite. Ellsworth county, Kansas.

2. In veins or vein-like deposits. Beaver county, Utah.

3. In cavities in limestone. Lockport, New York.

Kainite, $MgSO_4 \cdot KCl \cdot 3H_2O$

Form. Kainite usually occurs in granular masses.

H. = $2\frac{1}{2}$. **Sp. gr.** 2.1±.

Color, white, colorless, gray, or reddish.

Optical Properties. $n_\gamma(1.52) - n_\alpha(1.49) = 0.03$. Recrystallizes from water solution in the following order: (1) $K_2Mg(SO_4)_2 \cdot 6H_2O$, prismatic crystals with oblique extinction. (2) KCl, isotropic squares. (3) $MgSO_4 \cdot 7H_2O$ and $MgCl_2 \cdot 6H_2O$, confused streaky aggregates. Figure 495 represents the three stages of crystallization. The equation is $3(MgSO_4 \cdot KCl \cdot 3H_2O) + 10H_2O = K_2Mg(SO_4)_2 \cdot 6H_2O + KCl + MgSO_4 \cdot 7H_2O + MgCl_2 \cdot 6H_2O$.

FIG. 495.—Kainite recrystallized.

Chemical Composition. Hydrous magnesium sulfate and potassium chlorid. $MgSO_4 \cdot KCl \cdot 3H_2O$; ($H_2O$ = 21.7 per cent.).

Blowpipe Tests. Easily fusible (at 2), coloring the flame violet. In the closed tube gives water.

Soluble in water. The solution gives wet tests for Mg, SO_4, and Cl.

Distinguishing Features. Kainite is distinguished from halite and nitratine by the absence of cleavage and by the bitter taste.

Uses. Kainite is extensively used as a fertilizer and as a source of potassium salts. Stassfurt, Prussia, is practically the only producer.

Occurrence. 1. A secondary mineral of the Stassfurt salt deposits resulting from the action of magnesium sulfate on carnallite, ($KMgCl_3 \cdot 6H_2O$.).

Brochantite, $Cu_4(OH)_6SO_4$

Form. Brochantite is found in small prismatic crystals, in drusy crusts, and in fibrous masses.

H. = 3½. **Sp. gr.** 3.9±.

Color, emerald green.

Optical Properties. $n_\gamma(1.803) - n_\alpha(1.730) = 0.073$. Fragments are prismatic with parallel extinction.

Chemical Composition. Basic copper sulfate, $Cu_4(OH)_6SO_4$ or $CuSO_4 \cdot 3Cu(OH)_2$; (Cu = 56.2 per cent.; H_2O = 12 per cent.).

Blowpipe Test. Fusible at 3½. In the closed tube it turns black and gives off water.

Uses. At Chuquicamata, Chile, it is the principal ore of copper.

Insoluble in water. Soluble in HNO_3 *without* effervescence.

Distinguishing Features. Brochantite greatly resembles malachite. It is, however, soluble in acids without effervescence. From chalcanthite it is distinguished by the fact that it is not soluble in water.

Occurrence. 1. A secondary mineral associated with other copper minerals in the oxidized zone. Chuquicamata, Chile.

GYPSUM, $CaSO_4 \cdot 2H_2O$

Form. In form gypsum is variable. It occurs in embedded and attached crystals, in cleavage and crystalline masses, and in fibrous and granular masses.

Monoclinic system. Prismatic class: $\dot{a}:\bar{b}:\dot{c} = 0.689:1:0.412$; $\beta = 80°\ 42'$. Usual forms: $m\{110\}$, $l\{111\}$, $b\{010\}$, $e\{\bar{1}03\}$. Interfacial angles: $mm(110:1\bar{1}0) = 68°\ 30'$; $ll(111:1\bar{1}1) = 36°\ 12'$; $ml(110:111) = 49°\ 9'$; ae(edge $1\bar{1}0$–$\bar{1}\bar{1}0$:$\bar{1}03$) = 87° 49′. The habit is usually tabular parallel to the side pinacoid {010}. Figs. 496 to 498 represent typical crystals. Twins with {100} as twin-plane are common (Fig. 498).

Cleavage, perfect in one direction parallel to {010}, also imperfect conchoidal parallel to {100}, and fibrous parallel to

{$\bar{1}11$}. A cleavage fragment is oriented with respect to the crystal outline as shown in Fig. 499.

H. = 2 to 2½. **Sp. gr.** 2.3± .

Color, colorless, white, amber, gray, pink, etc. Luster, vitreous, silky, or pearly.

Optical Properties. n_γ(1.529) - n_a(1.520) = 0.009. Fragments are prismatic, acicular, or platy with bright interference colors and extinction angles of 0°, 13½°, or 37½°. Recrystallizes from dilute HCl solution as microchemical gypsum (Fig. 4, p. 43).

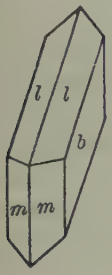


Fig. 496.

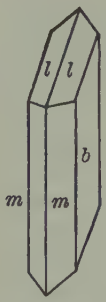


Fig. 497.

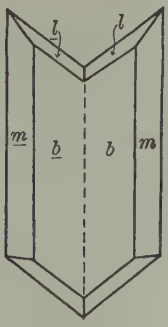


Fig. 498.

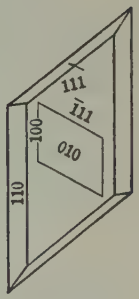


Fig. 499.

Figs. 496–499.—Gypsum.

Chemical Composition. Hydrous calcium sulfate, $CaSO_4 \cdot 2H_2O$; (H_2O = 20.9 per cent.). Massive gypsum may contain calcite, anhydrite, clay, sand, or organic matter.

Blowpipe Tests. Easily fusible (at 3) to a white enamel, giving a yellowish-red flame. In the closed tube it becomes opaque and gives off water at a low temperature.

Easily soluble in dilute HCl (distinction from anhydrite) and slightly soluble in water.

Distinguishing Features. Gypsum is distinguished from most minerals of similar appearance by its inferior hardness and low specific gravity. In addition, it is distinguished from anhydrite by its easy solubility, high water content, and by optical tests.

The optical tests are valuable, for gypsum and anhydrite can be recognized in the presence of each other.

Uses. Gypsum is extensively used as plaster and as a fertilizer to neutralize black alkali (sodium carbonate) in arid regions. France and the United States are the principal sources of gypsum. In this country, New York, Iowa, Michigan, and Ohio lead in the production.

Occurrence. 1. As bedded deposits associated with salt and limestone and formed directly by the evaporation of inland seas.

2. As a secondary mineral in various rocks formed principally by the action of sulfuric acid or ferrous sulfate (produced by the oxidation of pyrite) on calcium carbonate.

3. As a hydration product of anhydrite. At the Ludwig mine in Lyon county, Nevada, the hydration has reached a depth of 400 feet.

4. As gypsum earth (or gypsite) deposits formed by solution in fresh water and reprecipitation.

Chalcanthite, $CuSO_4 \cdot 5H_2O$

Form. Chalcanthite occurs as an incrustation or as fibrous seams. Artificial crystals of this substance furnish us excellent examples of triclinic crystals.

H. = $2\frac{1}{2}$. **Sp. gr.** $2.2\pm$.

Color, blue.

Optical Properties. $n_\gamma(1.54) - n_\alpha(1.51) = 0.03$. It recrystallizes from water solution in pale blue prismatic crystals with oblique extinction (10° to 15°).

Chemical Composition. Hydrous copper sulfate, $CuSO_4 \cdot 5H_2O$; (Cu = 25.4 H_2O = 36.1 per cent.). It often contains iron.

Blowpipe Tests. Fusible at 3. In the closed tube turns white, then black, and yields abundant water.

Soluble in water. The water solution placed on metallic iron (knife-blade) gives a film of copper.

Uses. In a few places it has been used in silver extraction.

Distinguishing Features. The color and disagreeable metallic taste are distinctive.

Occurrence. 1. A secondary mineral often found in abandoned mine drifts. The Bluestone mine in Lyon county, Nevada, is a prominent locality.

ALUNITE GROUP—HEXAGONAL

The following minerals form a well-defined isomorphous group:

Alunite,	$K_2Al_6(OH)_{12}(SO_4)_4$
Natroalunite,	$Na_2Al_6(OH)_{12}(SO_4)_4$
Jarosite,	$K_2Fe_6(OH)_{12}(SO_4)_4$
Natrojarosite,	$Na_2Fe_6(OH)_{12}(SO_4)_4$
Plumbojarosite,	$PbFe_6(OH)_{12}(SO_4)_4$
Carphosiderite,	$H_2Fe_6(OH)_{12}(SO_4)_4$

These minerals crystallize in the hexagonal scalenohedral class of the hexagonal system.

Some rare phosphate and sulfato-phosphate minerals are also probably isomorphous with the above listed minerals as has been shown by Schaller.

Alunite, $KAl_3(OH)_6(SO_4)_2$

Form. Alunite occurs in small crystals in cavities or disseminated through the rock mass occasionally in veins and often in fine grained masses. The crystals belong to the hexagonal system. The habit is usually tabular with the pinacoid $c\{0001\}$ and the rhombohedron $r\{10\bar{1}1\}$ as represented in Fig. 500.

H. = 4. **Sp. gr.** 2.8±.

Color, colorless, white, gray, or reddish.

Optical Properties. $n_\gamma(1.59) - n_\alpha(1.57) = 0.02$. Fragments are irregular with bright interference colors. Small crystals are triangular, dark between crossed nicols (basal sections), and give a positive uniaxial interference figure in convergent light.

Chemical Composition. Basic potassium aluminum sulfate, $KAl_3(OH)_6(SO_4)_2$ (K_2O = 11.4 per cent. H_2O = 13.0 per cent.). Sodium may replace part of the potassium.

Blowpipe Tests. Infusible and turns blue with cobalt nitrate solution. In the closed tube it gives water which has an acid reaction.

Soluble in H_2SO_4 with difficulty. It is insoluble in water, but after roasting it is converted into water-soluble alum.

Distinguishing Features. Alunite is difficult to recognize at sight.

Uses. Alum is obtained from the alunite rock by roasting and leaching with water. It has recently been mined near Marysvale, Utah.

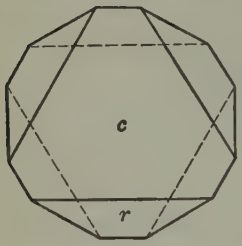


FIG. 500.—Alunite.

Occurrence. 1. A product of hydrothermal alteration, probably brought about by ascending acid solutions. Goldfield, Nevada.

Jarosite, $KFe_3(OH)_6(SO_4)_2$

Form. Jarosite occurs in small crystals in cavities or in massive to earthy forms. The crystals vary from hexagonal tabular to pseudo-cubic rhombohedral $(10\bar{1}1 - \bar{1}101) = 90°45'$. Figure 500 is a plan of a typical crystal with the forms $c\{0001\}$ and $r\{10\bar{1}1\}$.

H = 3. **Sp. gr.** = 3.2±.

Color, yellow to brown.

Optical Properties. $n_\gamma(1.77) - n_\alpha(1.74) = 0.03$. Fragments are irregular with third and fourth order interference colors, or are hexagonal tabular crystals and dark between crossed nicols.

Chemical Composition. Basic potassium ferric sulfate $KFe_3(OH)_6(SO_4)_2$·(H_2O = 10.8 per cent). Sodium or hydrogen may replace part of the potassium and thus it grades into natrojarosite and carphosiderite.

Blowpipe Tests. Fuses with difficulty (at 4.5) to a dark magnetic mass. In the closed tube turns dark and gives water which reacts acid to litmus paper.

Soluble in HCl to an amber-colored solution which reacts for ferric iron and the sulfate radical.

Distinguishing Features. The blowpipe and wet tests are distinctive.

Occurrence. 1. In the oxidized zone of ore-deposits. Tintic District, Utah.

2. In sedimentary rocks. Near Coalinga, California.

11. TUNGSTATES AND MOLYBDATES

Wolframite (Fe,Mn)WO_4

Scheelite Group	Scheelite,	$CaWO_4$
	Wulfenite,	$PbMoO_4$

WOLFRAMITE GROUP—MONOCLINIC

	FeO	MnO	WO_3
Ferberite (Colorado)	23.9	0.7	73.9
Wolframite (Burma)	13.8	9.4	74.8
Wolframite (Zinnwald)	9.6	14.8	75.6
Hübnerite (Colorado)	1.6	21.8	76.6

Wolframite, (Fe,Mn)WO_4

Form. Wolframite occurs in crystals and in crystalline aggregates. The crystals are monoclinic and are usually tabular parallel to {100}.

Cleavage, perfect in one direction parallel to {010}.

H. = 5 to 5½. **Sp. gr.** 7.4±.

Color, black or dark brown. Luster, sub-metallic. Opaque.

Chemical Composition. An isomorphous mixture of iron and manganese tungstates (Fe,Mn)WO_4, varying from $FeWO_4$ (ferberite) to $MnWO_4$(hübnerite) (WO_3 = 76.4 per cent.).

Blowpipe Tests. Fusible (at 3) to a magnetic globule. The sodium carbonate fusion is bluish-green (Mn).

Soluble in aqua regia with the separation of WO_3, a yellow residue.

Uses. Wolframite is the principal source of tungsten. Burma, the United States, and Portugal are the chief producers of wolframite.

Distinguishing Features. Wolframite is distinguished by its cleavage in one direction combined with its high specific gravity.

Occurrence. 1. A vein mineral especially in tin-stone veins associated with cassiterite, scheelite, etc. Zinnwald, Bohemia.
2. In granite pegmatites. Black Hills, South Dakota.

SCHEELITE GROUP—TETRAGONAL

Besides $CaWO_4$ (scheelite) and $PbMoO_4$ (wulfenite), there are also $CaMoO_4$ (powellite) and $PbWO_4$ (stolzite) which are similar crystallographically. Isomorphous replacement is illustrated by the following analyses:

	CaO	PbO	WO_3	MoO_3	Misc.
Scheelite (Carrock Fells)	19.3	....	80.0	0.3	
Scheelite (Zinnwald)	20.3	....	71.1	8.2	
Scheelite (Chili)	18.1	....	75.8	....	CuO = 3.3; SiO_2 = 0.7
Wulfenite (Eureka Co., Nevada)	1.0	61.1	. . .	39.3	Fe_2O_3 = 0.4

Scheelite, $CaWO_4$

Form. Scheelite occurs in both crystals and massive form. Crystals are tetragonal (Fig. 501) and belong to the tetragonal bipyramidal class (one plane of symmetry perpendicular to an axis of fourfold symmetry). The habit is pyramidal with $p\{111\}$ or $e\{101\}$ as the dominant form. Angles: $(111:\bar{1}11) = 79° 55\frac{1}{2}'$; $(101:011) = 72° 40\frac{1}{2}'$.

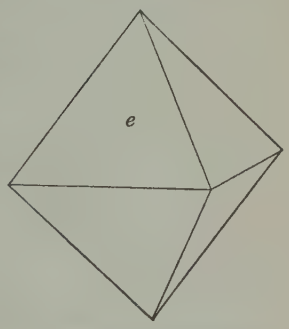


FIG. 501.—Scheelite.

Cleavage, distinct parallel to {011} (in four directions).

H. = $4\frac{1}{2}$ to 5. **Sp. gr.** 6.0±.

Color, white, gray, or pale colors. Luster, sub-adamantine.

Optical Properties. $n_\gamma(1.93) - n_\alpha(1.92) = 0.01$. Fragments are irregular with bright interference colors.

Chemical Composition. Calcium tungstate, $CaWO_4$; (WO_3 = 80.6 per cent.). The tungsten is often partially replaced by molybdenum. The copper in the third analysis above is due to partial alteration to cuprotungstite ($CuWO_4 \cdot 2H_2O$).

Blowpipe Tests. Fusible with difficulty (at 5). The $NaPO_3$ bead is blue in R.F.

Decomposed by HCl with the separation of a yellow residue (WO_3) soluble in NH_4OH.

Distinguishing Features. Scheelite is recognized by its high specific gravity and sub-adamantine luster.

Uses. Scheelite is one of the prominent ores of tungsten which is used to harden steel.

Atolia, San Bernardino county, California, is the chief producer of scheelite.

Occurrence. 1. In veins, especially in tin-stone veins with cassiterite, fluorite, topaz, etc.

Wulfenite, $PbMoO_4$

Form. Wulfenite usually occurs in crystals which are tetragonal and usually tabular in habit. Figure 502 is a plan of the common type of crystal with $c\{001\}$ and $u\{102\}$.

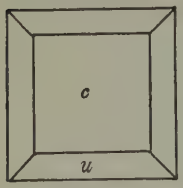


FIG. 502.—Wulfenite.

H. = 3 **Sp. gr.** 6.7±.

Color, yellow, orange, or red. Luster, adamantine.

Optical Properties. $n_\gamma(2.40) - n_\alpha(2.30) = 0.10$. Fragments are irregular and yellow with rather high interference colors. Thin tabular crystals give a negative uniaxial interference figure in convergent light.

Chemical Composition. Lead molybdate, $PbMoO_4$; (MoO_3 = 39.3 per cent.).

Blowpipe Tests. Easily fusible (at 2) on charcoal, giving a metallic button. The $NaPO_3$ bead is green in R.F.

Decomposed by HCl.

Distinguishing Features. Wulfenite is distinguished by its tabular crystals, yellow to red color, and adamantine luster.

Uses. Wulfenite is one of the sources of molybdenum.

Occurrence. 1. In the oxidized zone of veins often associated with vanadinite. Yuma county, Arizona.

12. SILICATES

Feldspars

- **ORTHOCLASE**, $(K,Na)AlSi_3O_8$
- **Adularia**, $KAlSi_3O_8$
- **Microcline**, $KAlSi_3O_8$
- **PLAGIOCLASE** ($Ab = NaAlSi_3O_8$; $An = CaAl_2Si_2O_8$)
  - **Albite**, Ab_{100} to $Ab_{90}\ An_{10}$
  - **Oligoclase**, $Ab_{90}Ab_{10}$ to $Ab_{70}\ An_{30}$
  - **Andesine**, $Ab_{70}\ An_{30}$ to $Ab_{50}\ An_{50}$
  - **Labradorite**, $Ab_{50}\ An_{50}$ to $Ab_{30}\ An_{70}$
  - **Bytownite**, $Ab_{30}\ An_{70}$ to $Ab_{10}\ An_{90}$
  - **Anorthite**, $Ab_{10}Ab_{90}$ to An_{100}

Feldspathoid Group

- **Leucite**, $KAl(SiO_3)_2$
- **Nepheline**, $(Na,K)AlSiO_4 \cdot (NaAlSi_3O_8)_x$
- **Sodalite**, $Na_4Al_3Cl(SiO_4)_3$
- **Lazurite**, $Na_5Al_3S(SiO_4)_3$

Pyroxene Group

- **Enstatite**, $MgSiO_3$
- **Hypersthene**, $(Mg,Fe)SiO_3$
- **PYROXENE**
  - **Diopside**, $Ca(Mg, Fe)(SiO_3)_2$
  - **Augite** $m\ CaMg(SiO_3)_2 + n(Mg,Fe)(Al,Fe)_2Si_2O_6$
- **Rhodonite**, $MnSiO_3$

Amphibole Group

- **Anthophyllite**, $(Mg,Fe)SiO_3$
- **Tremolite**, $Ca(Mg,Fe)_3(SiO_3)_4$
- **HORNBLENDE**, $mCa(Mg,Fe)_3(SiO_3)_4 + n(Al,Fe)(F,OH)SiO_3$
- **Glaucophane**, $NaAl(SiO_3)_2 \cdot (Fe,Mg)SiO_3$

- **Beryl**, $Be_3Al_2(SiO_3)_6$
- **Wollastonite**, $CaSiO_3$
- **Spodumene**, $LiAl(SiO_3)_2$

GARNET

- **Grossularite**, $Ca_3Al_2(SiO_4)_3$
- **Almandite**, $Fe_3Al_2(SiO_4)_3$
- **Pyrope**, $Mg_3Al_2(SiO_4)_3$
- **Andradite**, $Ca_3Fe_2(SiO_4)_3$

Olivine Group

- **OLIVINE**, $(Mg,Fe)_2SiO_4$
- **Forsterite**, Mg_2SiO_4

- **Willemite**, Zn_2SiO_4
- **CALAMINE**, $Zn_2(OH)_2SiO_3$
- **Scapolite**, $m(3CaAl_2Si_2O_8 \cdot CaCO_3) + n(3NaAlSi_3O_8 \cdot NaCl)$

Vesuvianite, $Ca_6Al_3(OH,F)(SiO_4)_5$
Zircon, $ZrSiO_4$
Topaz, $Al_2(F,OH)_2SiO_4$
Andalusite, Al_2SiO_5
Kyanite, Al_2SiO_5
Sillimanite, Al_2SiO_5

Epidote Group:
- EPIDOTE, $Ca_2(Al,Fe''')_3(OH)(SiO_4)_3$
- Clinozoisite, $Ca_2Al_3(OH)(SiO_4)_3$

Prehnite, $H_2Ca_2Al_2(SiO_4)_3$
Staurolite, $FeAl_5(OH)(SiO_6)_2$
TOURMALINE, $R_9Al_3B_2(OH)_2Si_4O_{19}$
Datolite, $CaB(OH)SiO_4$
Axinite, $HCa_2(Fe,Mn)Al_2B(SiO_4)_4$

Mica Group:
- MUSCOVITE, $H_2KAl_3(SiO_4)_3$
- Sericite, $H_2KAl_3(SiO_4)_3$
- Lepidolite, $LiKAl_2(OH,F)(SiO_3)_3$
- BIOTITE, $(HK)_2(Mg,Fe)Al_2(SiO_4)_3$
- Phlogopite, $H_2KMg_3Al(SiO_4)_3$

CHLORITE, $H_8(Mg\ Fe)_5Al_2(SiO_6)_3$
ANTIGORITE, $H_4Mg_3Si_2O_9$
Chrysotile, $H_4Mg_3Si_2O_9$
TALC, $H_2Mg_3(SiO_3)_4$
Chondrodite, $Mg_5(F,OH)_2(SiO_4)_2$
Kaolinite, $H_4Al_2Si_2O_9$
Halloysite, $H_4Al_2Si_2O_9 \cdot (H_2O)_x$
Garnierite, $H_2(Ni,Mg)SiO_4 \cdot H_2O$
CHRYSOCOLLA, $CuSiO_3 \cdot 2H_2O$?
Glauconite, $K\ Fe'''(SiO_3)_2 \cdot (H_2O)_x$?
Apophyllite, $(H,K)_2Ca(SiO_3)_4 \cdot H_2O$

ZEOLITES:
- Heulandite, $H_4CaAl(SiO_3) \cdot 3H_2O$
- Stilbite, $H_4(Ca,Na)(Al_2(SiO_3)_6 \cdot 4H_2O$
- Chabazite, $(Ca,Na_2)Al_2(SiO_3)_4 \cdot 6H_2O$
- Analcite, $NaAl(SiO_3)_2 \cdot H_2O$
- Natrolite, $Na_2Al_2Si_3O_{10} \cdot 2H_2O$

Titanite, $CaTiSiO_5$

About a fourth of the known minerals are silicates, though many of them are very rare. They are the most important rock-forming minerals and thus make up the bulk of the earth's outer shell. Among the important rock-making minerals are the feldspars, the pyroxenes, the amphiboles, and the micas. These,

together with quartz, constitute about 87 per cent. of the earth's outer shell, according to F. W. Clarke.

Many of the silicates are complex in composition and the establishment of chemical formulæ of some of them has baffled the skill of many eminent chemists. In a chemical discussion of the silicates the starting point is H_4SiO_4, which is called orthosilicic acid. The compound H_2SiO_3, derived thus ($H_4SiO_4 - H_2O = H_2SiO_3$), is called metasilicic acid. A large number of orthosilicates and metasilicates are known among minerals, but many silicates cannot be placed in either of these divisions; so the assumption has been made that other silicic acids are possible. Among them are $H_6Si_2O_7$ ($2H_4SiO_4 - H_2O$), diorthosilicic acid; $H_2Si_2O_5$ ($H_2SiO_3 + SiO_2$), dimetasilicic acid. In a similar way $H_4Si_3O_8$, $H_8Si_3O_{10}$, H_6SiO_5, and $H_{10}Si_2O_9$ may be derived. Minerals corresponding to all these acids are known.

Another method of nomenclature formerly used by chemists and still employed by metallurgists is based upon the ratio of the oxygen of silica to that of the bases. R_2SiO_4 may be written $2RO \cdot SiO_2$. Here the oxygen ratio is 1 : 1, so orthosilicates are called unisilicates. Metasilicates, $RSiO_3$ or $RO \cdot SiO_2$, are called bisilicates. Polysilicates have the formula $RO \cdot nSiO_2$ and subsilicates, $nRO \cdot SiO_2$, where n is greater than 2.

The difficulty of assigning formulæ to many silicate minerals lies in the fact that it is often impossible to decide upon the valence and grouping of the basic elements. Many silicates give water when heated in a closed tube, but it is often difficult and sometimes impossible to determine whether hydroxyl (OH), hydrion (H), or so-called water of crystallization (H_2O) is present. $H_2Zn_2SiO_5$ is the empirical formula for the mineral calamine. It may be an acid oxy-orthosilicate, $H_2(Zn_2O)SiO_4$, a basic metasilicate, $Zn_2(OH)_2SiO_3$, or an acid salt of H_6SiO_5, one of the possible silicic acids.

The silicates are treated as far as possible in more or less well-defined groups. Because of their importance the feldspars are given first.

FELDSPARS

A series of monoclinic and triclinic silicates of aluminum with either potassium, sodium, or calcium, collectively known as the feldspars, forms the most important group of rock-forming minerals. In fact feldspar is the most abundant substance of which we have direct knowledge, for it constitutes about 60 per cent. of the solid crust of the earth. The feldspars are non-metallic minerals with a hardness of about 6, and cleavage in two directions at, or nearly at, right angles, and a specific gravity of 2.6–2.7. The important feldspars are: orthoclase, adularia, and microcline, which are polymorphous forms of $KAlSi_3O_8$, and plagioclase, which is an isomorphous mixture of $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$.

The following are typical analyses of the various feldspars:

Analyses of the Feldspars

		K_2O	Na_2O	CaO	Al_2O_3	SiO_2	Misc.
	Orthoclase	11.7	4.3	0.5	18.8	64.6	BaO = 0.4; ign. = 0.1
	Adularia	14.0	1.0	1.3	17.9	65.7	Fe_2O_3 = tr.
	Microcline	13.5	1.6	....	19.6	64.8	ign. = 0.2
Plagioclase	Albite	0.5	11.1	0.4	19.3	68.8	Fe_2O_3 = 0.1
	Oligoclase	1.3	8.5	4.8	23.8	61.3	Fe_2O_3 = 0.4
	Andesine	1.0	6.2	8.1	26.6	58.0	
	Labradorite	tr	4.4	12.0	29.6	54.2	MgO = 0.1; ign. = 0.1
	Bytownite	0.6	1.8	16.1	31.1	46.9	Fe_2O_3 = 1.3; H_2O = 1.9
	Anorthite	....	0.2	19.3	36.8	44.0	MgO = 0.2; ign. = 0.1

ORTHOCLASE, $(K,Na)AlSi_3O_8$

Form. Orthoclase occurs in attached and embedded crystals, in cleavable masses, and disseminated through rock masses. The crystals furnish one of the best examples of the monoclinic prismatic class. Axial ratio: $\dot{a} : \bar{b} : \dot{c} = 0.658 : 1 : 0.555$; $\beta = 63° 57'$. Usual forms: $c\{001\}$, $b\{010\}$, $x\{\bar{1}01\}$, $y\{\bar{2}01\}$, $m\{110\}$, $z\{130\}$, $o\{\bar{1}11\}$, $n\{021\}$. Interfacial angles: $bc(010 : 001) = 90° 0'$; $mm(110 : 1\bar{1}0) = 61° 13'$; $mc(110 : 001) = 67° 47'$; *cx*-

$(001 : \bar{1}01) = 50°\ 16\frac{1}{2}'$; $cy(001 : \bar{2}01) = 80°\ 18'$; $mz(110 : 130) = 29°\ 59\frac{1}{2}'$; $bo(010 : \bar{1}11) = 63°\ 8'$; $cn(001 : 021) = 44°\ 56\frac{1}{2}'$. The habit is usually elongate in the direction of the *a*-axis (Figs. 503–505), or elongate in the direction of the *c*-axis and tabular parallel to {010} (Fig. 506).

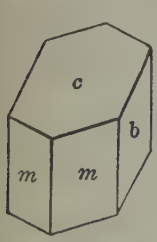


Fig. 503.

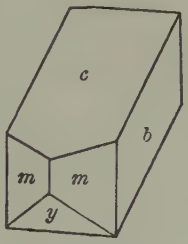


Fig. 504.

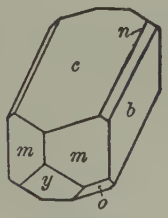


Fig. 505.

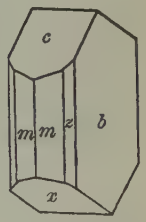


Fig. 506.

Figs. 503–506.—Orthoclase.

There are three common twinning laws for orthoclase: (1) the Carlsbad law in which the *c*-axis is the twin-axis (usually penetration twins with $b\{010\}$ as the composition face) (Fig. 507), (2) the Baveno law in which $n\{021\}$ is the twin-plane (Fig. 508),

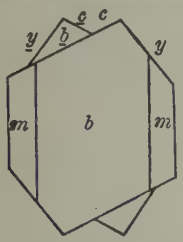


Fig. 507.

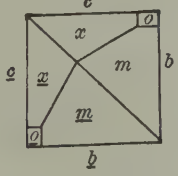


Fig. 508.

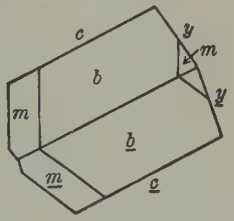


Fig. 509.

Figs. 507–509.—Orthoclase twins.

and (3) the Manebach law in which $c\{001\}$ is the twin-plane (Fig. 509).

Cleavage in two directions at right angles, parallel to {001} and {010}. There is also imperfect cleavage (or parting) parallel to {110} which assists in orienting cleavages and imperfect crystals.

H. = 6. **Sp. gr.** 2.57±.

Color, white, colorless, gray, pink, red. It sometimes shows a play of colors.

Optical Properties. $n_\gamma(1.526) - n_\alpha(1.519) = 0.007$. Fragments are plates usually with one set of parallel straight edges (Fig. 510). Extinction on 001 = 0°; on 010 = 5°. The interference colors are middle first-order (gray and straw-yellow).

Chemical Composition. Potassium aluminum trisilicate, (K, Na)$AlSi_3O_8$; (K_2O = 16.9, Al_2O_3 = 18.4, SiO_2 = 64.7 in $KAlSi_3O_8$.) Sodium replaces part of the potassium.

Blowpipe Tests. Fusible with difficulty (5). When fused with powdered gypsum on platinum wire it gives a violet flame. Insoluble in ordinary acids.

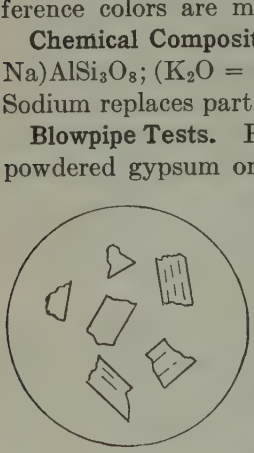


FIG. 510.—Orthoclase cleavage fragments.

Distinguishing Features. Distinguished from other minerals by rectangular cleavage and from minerals of the plagioclase group by the absence of twinning striations. Its distinction from microcline is difficult without optical tests.

Occurrence. 1. In acid plutonic igneous rocks, especially granites and syenites.

2. In acid volcanic igneous rocks, rhyolites and trachytes. This is usually sanidine, a transparent variety of orthoclase.

3. In certain rare basic igneous rocks.

4. In gneisses, partly as a remnant of igneous rocks, partly recrystallized.

5. In arkoses or feldspathic sandstones (Portland, Connecticut) and in some beach sands (Pacific Grove, California).

Adularia, $KAlSi_3O_8$

Form. Adularia occurs in distinct monoclinic crystals with practically the same forms and interfacial angles as orthoclase. The habit of the crystals is usually pseudo-orthorhombic because of the equal development of $c\{001\}$ and $x\{\bar{1}01\}$ (see Fig. 511) and as a consequence the cross section is rhombic.

Cleavage in two directions at right angles, parallel to {001} and {010}.

H. = 6 **Sp. gr.** 2.57±.

Color, colorless or white.

Optical Properties. $n_\gamma(1.524) - n_\alpha(1.518) = 0.006$. Fragments are plates with one set of parallel edges with extinction angles of 0° on 001, and 5° on 010.

Chemical Composition. Potassium aluminum silicate $KAlSi_3O_8$ (K_2O = 16.9 per cent.; Al_2O_3 = 18.4; SiO_2 = 64.7). Sodium is practically absent which fact distinguishes adularia from orthoclase.

Blowpipe Tests. Fusible with difficulty (at 5) to a colorless glass.

Insoluble in ordinary acids.

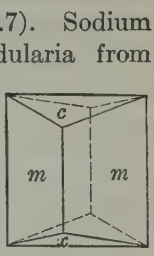


FIG. 511.—Adularia.

Distinguishing Features. Adularia can usually be distinguished from orthoclase by the crystal habit. The crystals have a rhombic cross section as the $b\{010\}$ face is absent or very narrow. Adularia is usually colorless and transparent, and orthoclase translucent.

Uses. A variety of adularia known as moonstone on account of its beautiful internal reflections is used as a gem. It is obtained in Ceylon.

Occurrence. 1. As a vein mineral formed at a comparatively low temperature in deposits near the surface which are gold- or silver-bearing. Guanajuato, Mexico.

2. In cavities and seams of schists and gneisses. Zillerthal, Tyrol.

Microcline, $KAlSi_3O_8$

Form. In crystal form microcline is almost like orthoclase, but it is triclinic with the angle (001 : 010) = 89° 30′ instead of 90°.

Cleavage. In two directions at practically right angles (89° 30′).

H. = 6. **Sp. gr.** 2.5±.

Color, white, gray, reddish, green. The green variety is called amazon-stone.

Optical Properties. $n_\gamma(1.529) - n_\alpha(1.522) = 0.007$. Extinction on 001 = 15°; on 010 = 5°. Fragments are plates with middle first-order interference colors, and are usually distinguished from orthoclase by the "gridiron" structure caused by polysynthetic twinning in two directions at right angles.

Chemical Composition. Potassium aluminum trisilicate $KAlSi_3O_8$, usually intergrown with albite, $NaAlSi_3O_8$ (Fig. 512). This intergrowth which is known as perthite or microperthite is probably formed by the unmixing of the solid solution, $(K,Na)AlSi_3O_8$, brought about by a lowering of the temperature.

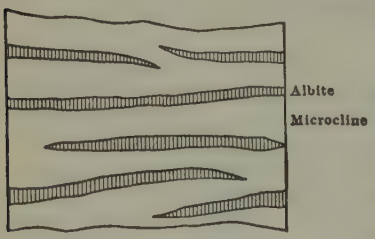


FIG. 512.—Microcline-albite intergrowth (perthite).

Blowpipe Tests. The same as for orthoclase.

Uses. The feldspar used in the manufacture of porcelain and pottery is largely the microcline-albite intergrowth known as perthite. Maine, North Carolina, and Pennsylvania are the principal producers.

Distinguishing Features. Microcline can often be distinguished from orthoclase by the fact that it is intergrown with albite. Otherwise it must be distinguished by optical tests.

Occurrence. 1. In granite pegmatites. Near Florissant, Colorado.

2. In granites (but not in rhyolites).

3. In gneisses.

PLAGIOCLASE

The plagioclase group of feldspars constitutes perhaps the best defined isomorphous group to be found among minerals. There is a perfect gradation in properties from the albite end of the group with the formula $NaAlSi_3O_8$ to the anorthite end of the

group with the formula $CaAl_2Si_2O_8$. Intermediate members of the group are designated by Ab_mAn_n; Ab denotes the albite

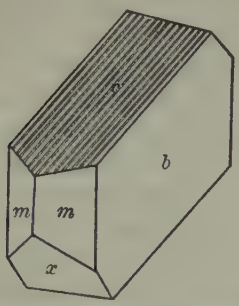


Fig. 513.—Albite twinning.

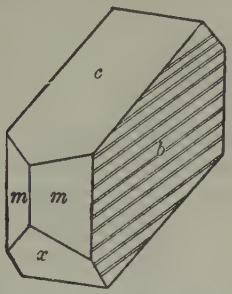


Fig. 514.—Pericline twinning.

molecule and An, the anorthite molecule. Crystals are triclinic, but with angles near those of orthoclase. The angle (001:010), for example, varies from 86° 24′ for albite to 85° 50′ for anorthite, while for orthoclase the corresponding angle is 90° 0′. The plagioclases have good cleavage parallel to {001}, and fair cleavage parallel to {010}. There is also imperfect cleavage parallel to {110} and $\{1\bar{1}0\}$.

Twinning is rarely absent in the plagioclases. The most common twinning is known as albite twinning, in which {010} is the twin-plane. This is usually polysynthetic and the twin striations, which are *always* parallel to the (001:010) edge, (Fig. 513) show best on the {001} cleavage face. Figure 515 shows in plan and elevation a cleavage fragment of plagioclase twinned on the albite law. The narrow planes marked 001 are placed at angles of about

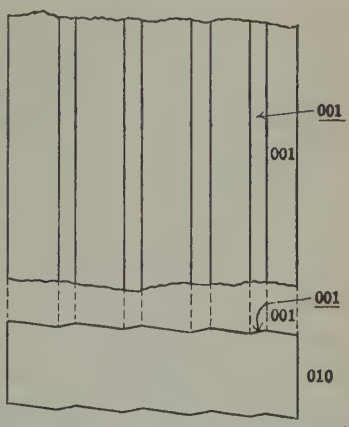


Fig. 515.—Plan and elevation of cleavage fragment of plagioclase twinned on {010}.

8° with the 001 planes. In pericline twinning, which is also polysynthetic, the *b*-axis is the twin-axis. This kind of twinning shows best on the {010} cleavage (Fig. 514), and the angle the striations make with the (001:010) edge differs for the various plagioclases. This angle is given in the column of the following tabulation labeled "angle of rhombic section." In optical properties the plagioclases are similar. They are all biaxial with $2V$ varying from 77° to 90°. The indices of refraction vary from 1.536 for albite to 1.588 for anorthite. The double refraction is rather weak (0.007 to 0.012). Typical analyses are given on page 344. The following tabulation illustrates the continuous variation in properties. The positive angles are clockwise and negative angles counter-clockwise.

		n_γ	n_α	Extinction on 001	Extinction on 010	Angle of rhombic section	Sp. gr.
Albite	Ab	1.536	1.525	+ 3½°	+23°	+22°	2.62
Oligoclase	Ab_9An_1	1.541	1.532	+ 2½	+15½	+10	2.64
Andesine	Ab_7An_3	1.552	1.545	0	0	+ 3	2.66
Labradorite	Ab_1An_1	1.562	1.555	− 4½	−16	− 1	2.69
Bytownite	An_3An_7	1.572	1.563	−14	−27	− 9	2.73
Anorthite	Ab_1An_9	1.582	1.571	−31	−36	−10	2.74
	An	1.588	1.576	−40	−37½	−16	2.76

Albite, Ab ($NaAlSi_3O_8$) to $Ab_{90}An_{10}$

Form. Albite occurs in small crystals, in lamellar masses, and intergrown with microcline. The crystals are triclinic, pinacoidal class, and are usually tabular parallel to {010}. The usual forms are the same as for orthoclase. Figure 513 represents the common type of crystal with $c\{001\}$, $b\{010\}$, $m\{110\}$, $M\{1\bar{1}0\}$, and $x\{\bar{1}01\}$. Albite, pericline, and Carlsbad twins are all common and sometimes two or more of these are combined on one crystal.

Cleavage, perfect parallel to {001} and less perfect parallel to {010}.

H. = 6. **Sp. gr.** 2.62±.

Color, white, colorless, or gray.

Optical Properties. n_γ(1.536 to 1.541) − n_α(1.525 to 1.532) = 0.009. Fragments are plates with middle first-order interference colors and extinction angles of about 3° on (001) and 15° to 23° on (010). The index of refraction is less than oil of cloves.

Chemical Composition. Ab_{100} to Ab_{90} An_{10}; (for $NaAlSi_3O_8$ Na_2O = 11.8, Al_2O_3 = 19.5, SiO_2 = 68.7). A little calcium is usually present as albite grades into oligoclase.

Blowpipe Tests. Fusible (at 4) to a colorless glass and colors the flame yellow.

Insoluble in ordinary acids.

Distinguishing Features. Albite may resemble barite but is distinguished by its greater hardness. From the other plagioclases it is only safely distinguished by optical tests.

Occurrence. 1. In granite pegmatites associated with tourmaline, lepidolite, spodumene, etc.

2. In veins and seams especially in the hydrothermal metamorphic rocks.

3. In certain soda-rich igneous rocks, usually intergrown with microcline. This intergrowth is known as *perthite.*

Oligoclase, $Ab_{90}An_{10}$ to $Ab_{70}An_{30}$

Form. Oligoclase occurs in cleavable masses and disseminated through rock masses, but unlike albite is rarely found in distinct crystals.

Cleavage, perfect parallel to {001}, less perfect parallel to {010}.

H. = 6. **Sp. gr.** 2.65 ±.

Color, white, colorless, greenish, or reddish.

Optical Properties. n_γ(1.541 to 1.552) − n_α(1.532 to 1.545) = 0.008. Fragments are plates with middle first-order interference colors and extinction angles of about 3° to 0° (001) and about 15½ to 0° (010). The fragments usually show polysynthetic twinning.

Chemical Composition. Sodium and calcium aluminum silicate, $Ab_{90}An_{10}$ to $Ab_{70}An_{30}$.

Blowpipe Tests. Fusible at 4.

Insoluble in ordinary acids.

Distinguishing Features. Distinguished from other plagioclasses by optical tests (or by a quantitative chemical analysis).

Occurrence. 1. In acid and intermediate igneous rocks, such as the granite-rhyolite series and the diorite-andesite series. Strange to say, oligoclase is more common in granites than albite.

Andesine, $Ab_{70}An_{30}$ to $Ab_{50}An_{50}$

Form. Andesine occurs in cleavable masses or disseminated crystals through rock masses. Distinct loose crystals are rare.

Cleavage, in two directions at angles of 86° 14′.

H = 6. **Sp. gr.** 2.69±.

Color, colorless, white, and various tints.

Optical Properties. n_γ(1.552 to 1.562) − n_α(1.545 to 1.555) = .007. Fragments are plates with middle first-order interference colors and extinction angles of 0 to 4½° on (001) and 0° to 16° on (010). They usually show polysynthetic twinning.

Chemical Composition. Sodium and calcium aluminum silicate, $Ab_{70}An_{30}$ to $Ab_{50}An_{50}$.

Blowpipe Tests. Fusible (at 4). Insoluble in ordinary acids.

Distinguishing Features. Distinguished from the other plagioclases by optical tests (or by a quantitative chemical analysis).

Occurrence. 1. In intermediate igneous rocks such as diorites and andesites.

Labradorite, $Ab_{50}An_{50}$ to $Ab_{30}An_{70}$

Form. Labradorite occurs in embedded crystals and in cleavable masses, but very rarely in distinct loose crystals. Albite twinning is the common kind of twinning.

Cleavage, perfect parallel to {001}, less perfect parallel to {010}.

H. = 6. **Sp. gr.** 2.71±.

Color, gray or white, often showing a play of colors which is an optical effect due to minute inclusions.

Optical Properties. n_γ(1.562 to 1.572) − n_α(1.555 to 1.563) = 0.009. Fragments are plates with middle first-order interference colors and extinction angles of $-4\frac{1}{2}°$ to $-14°$ (001) and $-16°$ to $-27°$ (010). The fragments usually show polysynthetic twinning and often minute inclusions arranged in rows.

Chemical Composition. Calcium-sodium aluminum silicate, $Ab_{50}An_{50}$ to $Ab_{30}An_{70}$.

Blowpipe Tests. Fusible at 4.

Soluble with difficulty in HCl.

Distinguishing Features. Labradorite is distinguished from orthoclase by the twinning striations on the cleavage surfaces.

Uses. Labradorite rock is used as an ornamental stone.

Occurrence. 1. In basic igneous rocks such as gabbros, diabases, and basalts, associated with olivine, augite, hypersthene, ilmenite, and magnetite.

2. As the principal constituent of anorthosite, a basic plutonic igneous rock composed practically of labradorite. Adirondack Mts., New York.

Bytownite, $Ab_{30}An_{70}$ to $Ab_{10}An_{90}$

Form. In cleavable masses and disseminated through rock like the other plagioclases.

Cleavage, in two directions at angles of about 86°.

H. = 6. **Sp. gr.** 2.74±.

Color. Colorless, white, or gray.

Optical Properties. n_γ (1.572 to 1.582) − n_α(1.563 to 1.571) = .010. Fragments are plates with upper first-order interference colors and extinction angles of 14° to 31° on (001) and 27° to 36° on (010).

Chemical Composition. Calcium and sodium aluminum silicate, $Ab_{30}An_{70}$ to $Ab_{10}An_{90}$.

Blowpipe Tests. Fusible at $4\frac{1}{2}$.

Slightly soluble in HCl.

Distinguishing Features. Bytownite can be distinguished

from labradorite only by optical tests (or by a quantitative chemical analysis).

Occurrence. 1. In basic igneous rocks especially gabbros. Duluth, Minnesota.

Anorthite, $Ab_{10}An_{90}$ to An ($CaAl_2SiO_8$)

Form. Anorthite occurs in cleavable masses and occasionally in euhedral crystals.

Cleavage. Like the other plagioclase feldspars, in two directions at angles of about 86°.

H. = 6. **Sp. gr.** 2.76±.

Color, white, gray, or reddish.

Optical Properties. n_γ(1.582 to 1.588) − n_α(1.571 to 1.576) = .012. Fragments are plates with upper first-order interference colors and extinction angles of 31° to 40° on (001) and 36° to 37½° on (010).

Chemical Composition. Calcium aluminum silicate, usually with a little sodium, Ab_{10} An_{90} to An $_{100}$. (For An, CaO = 20.1; Al_2O_3 = 36.7; SiO_2 = 43.2.)

Blowpipe Tests. Fusible at 4½.

Slowly soluble in HCl and gives a jelly of silicic acid upon evaporation.

Distinguishing Features. Optical tests (or a quantitative chemical analysis) are necessary to distinguish anorthite from other members of the plagioclase group.

Occurrence. 1. A comparatively rare mineral in basic igneous rocks. Miyake, Japan.

FELDSPATHOID GROUP

Leucite, nepheline, sodalite, and lazurite are collectively known as feldspathoids, for they are alkaline aluminum silicates which play the same rôle in some rare igneous rocks that the feldspars do.

Leucite, $KAl(SiO_3)_2$

Form. For leucite the characteristic form is well-defined embedded crystals. The crystals are isometric; the only common form is the trapezohedron {211} (Fig. 516). Cross-sections are eight-sided (Fig. 517).

H. = 5½ to 6. **Sp. gr.** 2.5±.

Color, white or gray.

Optical Properties. n = 1.50. Isotropic. Fragments are irregular and are either dark between crossed nicols or have very low first-order interference colors.

Chemical Composition. Potassium aluminum metasilicate $KAl(SiO_3)_2$. (K_2O = 21.5 per cent.). A little sodium is sometimes present.

Blowpipe Tests. Infusible.

Decomposed by HCl with the separation of powdery silica.

Distinguishing Features. Leucite is distinguished by its equidimensional crystals, which are never formed in cavities.

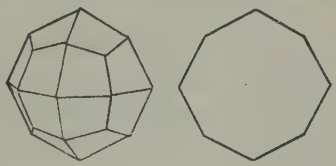


Fig. 516. Fig. 517.

Figs. 516–517.—Leucite.

Uses. Rocks containing large amounts of leucite are a possible source of potassium salts.

Occurrence. 1. In certain volcanic rocks in which leucite takes the place of the feldspars or occurs with feldspars. (Exceedingly rare in plutonic rocks.) Leucite is rare in the United States, but occurs in large quantities in the Leucite Hills, Wyoming.

Nepheline, $(Na,K)AlSiO_4 \cdot (NaAlSi_3O_8)_x$

Form. Nepheline occurs in embedded crystals or grains and in massive forms. Crystals are hexagonal, and short prismatic in habit. The cross-sections are six-sided and rectangular.

H. = 5½ to 6. **Sp. gr.** 2.6±.

Color, white, gray, or reddish. Luster, greasy.

Optical Properties. $n_\gamma(1.543) - n_\alpha(1.538) = 0.005$. Fragments are irregular with low first order interference colors.

Chemical Composition. Essentially sodium aluminum orthosilicate, $NaAlSiO_4$, but with an excess of silica which is probably present as $NaAlSi_3O_8$. Potassium replaces part of the sodium.

Blowpipe Tests. Fuses at 4 to a colorless glass.

Gelatinizes with HCl.

Distinguishing Features. Nepheline resembles quartz but is distinguished by its inferior hardness. It lacks the cleavage of the feldspars.

Occurrence. 1. In nepheline syenites, phonolites, and other rare soda-rich igneous rocks. It is often associated with orthoclase, but never with quartz. Magnet Cove, Arkansas.

Sodalite, $Na_4Al_3Cl(SiO_4)_3$

Form. Sodalite usually occurs in disseminated or massive forms, but isometric dodecahedral crystals are sometimes found.

Cleavage, indistinct dodecahedral.

H. = 5½ to 6. **Sp. gr.** 2.3±.

Color, blue, gray, or colorless.

Optical Properties. $n = 1.483$. Isotropic. Fragments are irregular and colorless, and dark between crossed nicols.

Chemical Composition. Sodium aluminum chlorid and orthosilicate, $Na_4Al_3Cl(SiO_4)_3$ or $3NaAlSiO_4 \cdot NaCl$.

Blowpipe Tests. Fusible with intumescence to a colorless glass. The $NaPO_3$ bead with CuO gives an azure blue flame.

Gelatinizes with HCl.

Distinguishing Features. Blue sodalite is distinguished from lazurite by the absence of associated pyrite. Unless it shows the blue color, it is a difficult mineral to recognize. The chlorin test in a $NaPO_3$ bead will distinguish it from most other minerals.

Uses. Some varieties of sodalite rocks are used for ornamental stones.

Occurrence. 1. In soda-rich igneous rocks such as nepheline syenites and phonolites.

Lazurite, $Na_5Al_3S(SiO_4)_3$

Form. Lazurite usually occurs in compact massive form, more or less mixed with calcite, pyrite, and other silicates. This mixture is known as *lapis lazuli.*

H. = 5 to 5½. **Sp. gr.** 2.4±.

Color, deep blue. Streak, pale blue.

Optical Properties. *n* about 1.50. Isotropic. Fragments are irregular, deep blue, non-pleochroic, and dark between crossed nicols.

Chemical Composition. Sodium aluminum sulfid and orthosilicate, $Na_5Al_3S(SiO_4)_3$ or $3NaAlSiO_4 \cdot Na_2S$. It usually contains calcium and the sulfate radical, both due to isomorphous replacement.

Blowpipe Tests. Fuses (at 3) with intumescence to a white glass.

Soluble in HCl with gelatinization and with the evolution of H_2S.

Distinguishing Features. Lazurite, or more properly lapis-lazuli, is distinguished by its blue color and by the presence of pyrite. The latter also distinguishes it from imitation stones.

Uses. Lapis lazuli is a valuable ornamental stone. It was the "sapphire" of the ancients. The paint called ultramarine was formerly lapis lazuli, but it is now made artificially.

Occurrence. 1. As a contact mineral in crystalline limestones associated with diopside and other silicates. The quarries at Badakshan in Afghanistan, the principal source of lapis lazuli, are the oldest known mines in existence.

PYROXENE GROUP

The following minerals constitute a mineral group, though they are not strictly isomorphous; for enstatite and hypersthene are orthorhombic and rhodonite is triclinic, while the others are monoclinic.

Typical analyses of the more important members of the pyroxene group are given in the following tabulation.

Analyses of Minerals of the Pyroxene Group

	MgO	FeO	CaO	Al_2O_3	Fe_2O_3	SiO_2	Misc.
Enstatite	36.9	3.2	....	1.3	...	58.0	ign. = 0.8
Bronzite	29.7	10.1	....	1.3	...	58.0	MnO = 1.0
Hypersthene	21.3	21.3	3.1	0.4	...	51.4	
Diopside	17.3	1.9	25.0	0.5	1.0	54.8	
Diopside	16.1	5.0	24.9	1.5	0.6	52.8	
Diopside	10.0	12.3	22.1	2.0	1.3	51.1	MnO = 0.1; ign. = 0.3
Diallage	16.4	8.4	20.3	3.8	...	50.2	
Augite	16.0	4.1	19.0	9.8	4.5	46.9	
Augite	7.6	9.4	12.3	21.5	3.8	42.2	Na_2O = 3.0
Augite	13.2	4.3	21.3	8.2	3.7	46.5	TiO_2 = 2.8

Enstatite, $MgSiO_3$

Form. Enstatite usually occurs in lamellar or fibrous-lamellar masses. The mineral is orthorhombic, but distinct crystals are very rare.

Cleavage, distinct in several directions.

H. = $5\frac{1}{2}$ to 6. **Sp. gr.** $3.3\pm$.

Color, bronze, gray, or brown. Luster, metalloidal.

Optical Properties, $n_\gamma(1.67) - n_\alpha(1.66) = 0.01$. Fragments are prismatic with parallel extinction, low first order interference colors, and positive elongation.

Chemical Composition. Magnesium metasilicate; (MgO = 40.0 per cent.). Ferrous iron usually replaces part of the magnesium. Ferriferous enstatite is called *bronzite.*

Blowpipe Tests. Fusible on thin edges (at 6).

Insoluble in acids.

Distinguishing Features. Enstatite can usually be distinguished by its peculiar bronze-yellow, but non-metallic, appearance.

Occurrence. 1. In basic igneous rocks such as peridotites and gabbros.

2. In meteorites.

Hypersthene, $(Fe,Mg)SiO_3$

Form. Hypersthene usually occurs in cleavable masses or is disseminated through rock masses.

Cleavage, good cleavage in one direction.

H. = 5½. **Sp. gr.** 3.4±.

Color, dark brown or greenish brown.

Optical Properties. $n_\gamma(1.70) - n_\alpha(1.69) = 0.01$. Fragments are prismatic with parallel extinction, bright interference colors, and positive elongation. Hypersthene is usually pleochroic; it changes from pink to green.

Chemical Composition. Iron and magnesium metasilicate, $(Fe,Mg)SiO_3$.

Blowpipe Tests. Fusible (at 5) to a black glass. On charcoal in R.F. it becomes magnetic.

Soluble with difficulty in HCl.

Distinguishing Features. Hypersthene is difficult to distinguish without optical tests.

Occurrence. 1. In basic igneous rocks, especially gabbros and norites.

PYROXENE

On account of the difficulty of distinguishing some of the members of the pyroxene group they are often grouped under

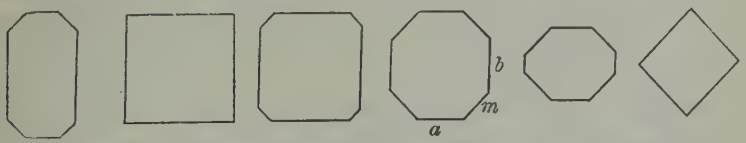


Fig. 518.—Cross-sections of pyroxene (diopside and augite).

the name, common pyroxene or pyroxene proper. Pyroxene (in this sense) is a silicate of aluminum, iron, calcium, and magnesium, which is often found in monoclinic prismatic crystals (see Figs. 519–526) with the typical cross-sections shown in Fig. 518. It comprises two fairly well-defined minerals, diopside and augite.

Diopside, $Ca(Mg,Fe)(SiO_3)_2$

Form. In crystals, granular masses, disseminated through rocks, but rarely fibrous or columnar.

Monoclinic system.—Prismatic class. $\dot{a} : \bar{b} : \dot{c} = 1.092 : 1 : 0.589$; $\beta = 74° 10'$. Usual forms: $a\{100\}$, $b\{010\}$, $m\{110\}$, $c\{001\}$, $p\{111\}$, $o\{\bar{2}21\}$, $\Delta\{\bar{3}11\}$, $d\{\bar{1}01\}$. Interfacial angles: $mm(110 : 1\bar{1}0) = 92° 50'$; $pp(111 : 1\bar{1}1) = 48° 29'$; $oo(\bar{2}21 : \bar{2}\bar{2}1) = 84° 11'$.

The habit is usually prismatic in the direction of the *c*-axis. Figs. 519 to 522 represent typical crystals. The cross-section of

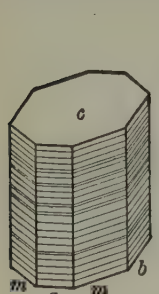


Fig. 519.

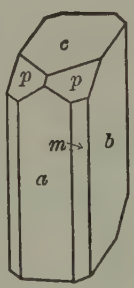


Fig. 520.

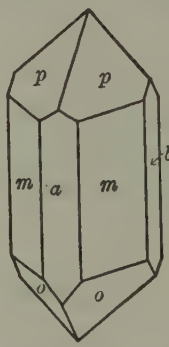


Fig. 521.

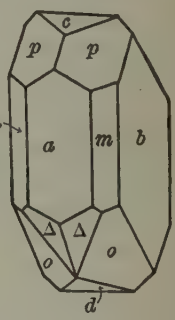


Fig. 522.

Figs. 519–522.—Diopside.

crystals is characteristic; it is usually four- or eight-sided as represented in Fig. 518.

Cleavage, imperfect in two directions at angles of 87° 10′ and 92° 50′ (parallel to the unit prism {110}). There is often parting parallel to {001} which is more prominent than the cleavage. The variety *diallage* has well-defined parting parallel to {100}.

H. = 4 to 6. **Sp. gr.** 3.2±.

Color, white, gray, or green.

Optical Properties. $n_\gamma(1.70) - n_\alpha(1.67) = 0.03$. Fragments are prismatic and colorless or pale green with bright interference colors and an extinction angle of 20°–30°. A thin parting flake

parallel to {001} will give an interference figure consisting of an axial bar with concentric rings. Diallage has parallel extinction and positive elongation.

Chemical Composition. Calcium magnesium-ferrous metasilicate varying from $CaMg(SiO_3)_2$ to $CaFe(SiO_3)_2$. Small amounts of aluminum, ferric iron, and manganese may also be present.

Blowpipe Tests. Fusible at 4 to a colorless or pale green glass. Insoluble in acids.

Distinguishing Features. Diopside is distinguished by its crystal form and imperfect prismatic cleavage. It is usually distinguished from augite by basal parting and lighter color.

Occurrence. 1. In crystalline limestones as a contact mineral associated with garnet.

2. In schists and other metamorphic rocks, both in the rock mass and in seams.

3. In gabbros and peridotites (the variety diallage).

Augite, $m\mathbf{CaMg}(\mathbf{SiO_3})_2 + n(\mathbf{Mg,Fe})(\mathbf{Al,Fe})_2\mathbf{SiO_6}$

Form. Augite usually occurs in embedded crystals. The crystals are monoclinic, prismatic class, with the forms: $a\{100\}$, $b\{010\}$, $m\{110\}$, $s\{\bar{1}11\}$. Interfacial angles: $mm(110:1\bar{1}0) = 92° 50'$, $ss(\bar{1}11:\bar{1}\bar{1}1) = 59° 11'$. The habit is usually prismatic (Figs. 523–526) and either square or octagonal in outline (see Fig. 518). Twins with $a\{100\}$ as twin-plane are common (Fig. 526).

Cleavage, imperfect in two directions parallel to {110}, and at angles of 92° 50′ and 87° 10′.

H. = 5½. **Sp. gr.** 3.3±.

Color, dark green to black.

Optical Properties. $n_\gamma(1.73) - n_\alpha(1.71) = 0.02$. Fragments are prismatic with bright interference colors and large extinction angles (25° to 40°). The thin fragments are only slightly pleochroic, if at all. This usually distinguishes augite from hornblende.

Chemical Composition. An isomorphous mixture of $CaMg(SiO_3)_2$ and $(Mg,Fe)(Al,Fe)_2SiO_6$ in varying proportions. The presence of aluminum and ferric iron distinguishes augite from diopside. Sodium and titanium are sometimes present.

Blowpipe Tests. Fusible at 4 to a black glass.

Insoluble in acids.

Distinguishing Features. Augite is distinguished from hornblende by its square or octagonal cross-section and imperfect prismatic cleavage. It is darker colored than diopside.

Occurrence. 1. In basic igneous rocks, especially basalts and diabases, often as phenocrysts like Figs. 523–526. Bohemia.

2. In basaltic tuffs.

Fig. 523.

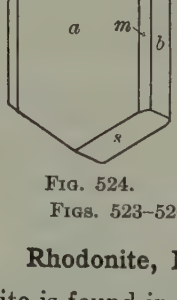


Fig. 524.

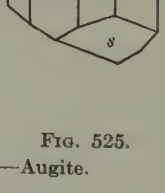


Fig. 525.

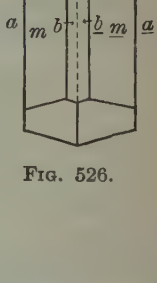


Fig. 526.

Figs. 523–526.—Augite.

Rhodonite, $MnSiO_3$

Form. Rhodonite is found in cleavable and compact masses, and occasionally in euhedral crystals. The crystals are triclinic, but similar to diopside and augite in angles.

Cleavage, in two directions at angles of 92½° (parallel to 110) and also an additional parting parallel to (100); the angle (100:110) is 48° 33′.

H. = 5½. **Sp. gr.** 3.6±.

Color, pink or red, often stained black by manganese oxids.

Optical Properties. $n_\gamma(1.74) - n_\alpha(1.72) = 0.02$. Fragments are prismatic with bright interference colors and large extinction angles (20 to 25°).

Chemical Composition. Manganese metasilicate, $MnSiO_3$. Calcium is usually present and sometimes iron.

Blowpipe Tests. Fusible at 3 to a dark glass.

Partially soluble in HCl.

Distinguishing Features. Rhodonite is distinguished from orthoclase and microcline by its high specific gravity and from rhodochrosite by its greater hardness.

Uses. Conpact rhodonite is used as an ornamental stone, especially in Russia.

Occurrence. 1. In high-temperature veins with garnet. Broken Hill, New South Wales.

2. In crystalline limestones with willemite, franklinite, and zincite. Franklin Furnace, New Jersey.

AMPHIBOLE GROUP

The amphibole group is parallel to the pyroxene group, but the triclinic members are so rare that no account of them will be given here. The amphiboles differ from the pyroxenes mainly in the prism and cleavage angle, which is 56°(and 124°) instead of 87° (and 93°). For many of the pyroxenes there are corresponding amphiboles, but they cannot be regarded as dimorphous minerals. For example, diopside is $CaMg(SiO_3)_2$, while the corresponding tremolite is $CaMg_3(SiO_3)_4$. Tremolite and hornblende contain a small amount of water of constitution, while diopside and augite, if unaltered, contain none.

Analyses of Amphiboles

	CaO	MgO	FeO	Al_2O_3	Fe_2O_3	SiO_2	TiO_2	H_2O	Na_2O	K_2O	F
Anthophyllite..	0.2	28.7	10.4	0.6	...	58.0	...	1.7	...	...	...
Tremolite.....	13.2	24.1	0.6	1.8	...	57.7	0.1	1.6	0.5	0.2	0.4
Tremolite (actinolite).....	12.1	21.2	5.5	1.2	0.8	56.3	...	1.8	0.2	0.3	0.1
Hornblende....	9.8	12.6	10.5	8.3	6.9	43.8	0.8	0.6	3.4	1.3	1.8
Hornblende....	11.5	11.2	14.3	11.6	2.7	42.0	1.5	0.6	2.5	0.1	0.8
Hornblende....	12.0	14.2	2.2	17.6	7.2	39.9	1.7	0.4	3.2	0.2	0.1

Anthophyllite, $(Mg,Fe)SiO_3$

Form. Anthophyllite usually occurs in lamellar, fibrous, or asbestiform masses, which are often radiating. Crystals are orthorhombic but terminal faces have never been found.

Cleavage, perfect in two directions at angles of 54° and 126°.

H. = 5–6. **Sp. gr.** = 3.1±.

Color, gray to brown.

Optical Properties. $n_\gamma(1.657) - n_\alpha(1.633) = 0.025$. Fragments are prismatic with parallel extinction and positive elongation. The interference colors range up to low second-order.

Chemical Composition. Magnesium, iron metasilicate (Mg,Fe) SiO_3. Aluminum is often present and in one variety (gedrite) is prominent. Most specimens of anthophyllite contain a little water. A typical analysis is given on page 363.

Blowpipe Tests. Anthophyllite is fusible on thin edges to a black glass. In the closed tube it may give a little water.

Insoluble in acids.

Distinguishing Features. Anthophyllite is distinguished from the other amphiboles by the absence of calcium and by the parallel extinction in fragments.

Uses. Anthophyllite in its finely fibrous form is one of the varieties of asbestos. It is quarried at Salls Mountain, Georgia.

Occurrence. 1. A typical metamorphic mineral occurring in schists and gneisses.

Tremolite, $Ca(Mg,Fe)_3(SiO_3)_4$

Form. Tremolite occurs in long prismatic crystals and in columnar and fibrous aggregates. Crystals are monoclinic with the prism {110} and the pinacoid {010}, but rarely have terminal faces. The axial ratios and interfacial angles are like those of hornblende. Characteristic cross-sections are shown in Fig. 527.

Cleavage, in two directions at angles of 56° and 124° parallel to {110}. The cleavage is more perfect than that of diopside.

H. = 5½. (Fibers may appear to be lower). **Sp. gr.** 3.0±.

Color, white, gray, or green. The green varieties are sometimes called actinolite.

Optical Properties. $n_\gamma(1.636) - n_\alpha(1.611) = 0.025$. Fragments are prismatic or acicular with bright interference colors, positive elongation, and extinction angles of 10° to 15°.

Chemical Composition. Calcium magnesium-iron metasilicate $Ca(Mg,Fe)_3(SiO_3)_4$. Ferriferous varieties with more than 2 or 3 per cent. of FeO are called **actinolite.** Aluminum and ferric iron are very low and this is the principal chemical distinction between these minerals and hornblende.

Blowpipe Tests. Fusible at 4 to a glass.

Insoluble in acids.

Distinguishing Features. Tremolite is easily recognized in typical specimens by its characteristic cleavage. It is distin-

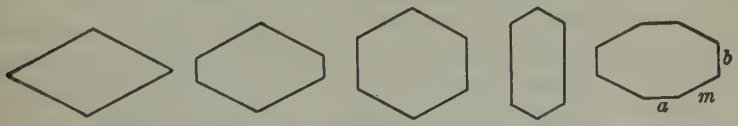


FIG. 527.—Cross-sections of tremolite (inc. actinolite) and hornblende.

guished from hornblende only by its color, and optical characters.

Uses. The fibrous tremolite is one kind of asbestos.

Occurrence. 1. In crystalline dolomitic limestones. Lee, Massachusetts.

2. In schists, often associated with talc. St. Lawrence County, New York.

3. As a hydrothermal alteration product of pyroxene. This is a fibrous variety known as **uralite** which usually contains some iron and aluminum and thus grades into hornblende.

HORNBLENDE, $m\mathbf{Ca(Mg,Fe)_3(SiO_3)_4}+n\mathbf{(Al,Fe)(F,OH)SiO_3}$

Form. Hornblende occurs in well-defined crystals, in cleavages, in disseminated crystals and grains, and in bladed aggregates.

Monoclinic system. Prismatic class. Axial ratio: $\dot{a} : \bar{b} : \dot{c} =$

0.551 : 1 : 0.293; $\beta = 73° 58'$. Usual forms: $m\{110\}$, $b\{010\}$, $a\{100\}$, $r\{011\}$, $p\{\bar{1}01\}$. Interfacial angles: $mm(110 : 1\bar{1}0) = 55° 49'$, $rr\{011 : 0\bar{1}1\} = 31° 32'$, $rp\{011 : \bar{1}01\} = 34° 25'$. Habit short to long prismatic, usually pseudohexagonal or rhombic in cross-section. (See Fig. 527.) The common type of hornblende crystal is that of Fig. 528.

Cleavage, perfect in two directions at angles of 56° and 124°, parallel to {110}.

H. = 5½. **Sp. gr.** 3.2±.

Color, dark green, or dark brown to black.

Optical Properties, $n_\gamma(1.653) - n_\alpha(1.629) = 0.024$. Fragments are prismatic, and green or brown in color. The extinction angle varies from 5° to 20° and the elongation is positive. Pleochroism is a marked feature of hornblende. The colors vary from pale to deep green, from yellowish-green to bluish-green, from brown to greenish-brown, or from pale to deep brown. By the pleochroism and the extinction angle, hornblende may easily be distinguished from augite, which it often greatly resembles.

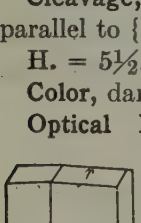


FIG. 528.—Hornblende.

Chemical Composition. A complex metasilicate of calcium, magnesium, ferrous iron, aluminum, and ferric iron with fluorin and hydroxyl. The formula given above was established by Penfield and Stanley (see analyses, page 363).

Blowpipe Tests. Fusible at 4 to a black glass. In the closed tube it gives a little water at a high temperature.

Insoluble in acids.

Distinguishing Features. Hornblende is distinguished from pyroxene by its six-sided cross-section and by its perfect prismatic cleavage of 56°. Optical tests may be necessary to distinguish hornblende from pyroxene.

Occurrence. 1. In volcanic igneous rocks such as andesites and certain basalts.

2. In plutonic igneous rocks, especially granites, syenites, and diorites, rarely in gabbros and peridotites.

3. In diabases and gabbros as a magmatic alteration product of augite and other pyroxenes.

4. In schists and gneisses often forming rock masses, hornblende schists and amphibolites.

Glaucophane, $NaAl(SiO_3)_2 \cdot (Fe,Mg)SiO_3$

Form. Glaucophane occurs in small disseminated crystals and in fibrous masses. Crystals are prismatic in habit with {100}, {010}, and {110}, but are rarely terminated. The cross-section

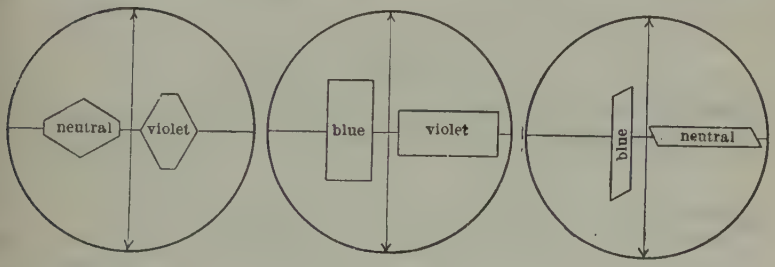


FIG. 529. FIG. 530. FIG. 531.

FIGS. 529–531.—Pleochroism of glaucophane.

as seen in thin rock sections is pseudohexagonal or rhombic (Fig. 527).

Cleavage, parallel to {110}, *i.e.*, in two directions at angles of 56° and 124°.

H. 6 to 6½. **Sp. gr.** 3.1±.

Color, blue to blue-black.

Optical Properties. $n_\gamma(1.64) - n_\alpha(1.62) = 0.02$. Fragments are prismatic and blue in color with pleochroism from blue to violet. The extinction is practically parallel and the elongation positive.

In thin sections glaucophane shows the pleochroism illustrated by Figs. 529–531.

Chemical Composition. Sodium, aluminum, iron-magnesium metasilicate, $NaAl(SiO_3)_2 \cdot (Fe,Mg)SiO_3$. Glaucophane is one of the group known as soda amphiboles.

Blowpipe Tests. Easily fusible (at 3) to a dark glass; gives an intense yellow flame.

Insoluble in acids.

Distinguishing Features. The blue to blue-black color and occurrence in schists are distinctive.

Occurrence. 1. In schists and gneisses often constituting the main part of the rock. Glaucophane schists and glaucophane gneisses are especially abundant in the Coast Ranges of California.

Beryl, $Be_3Al_2(SiO_3)_6$

Form. For beryl the characteristic forms are crystals and columnar masses. Beryl crystallizes in the hexagonal system,

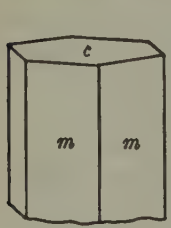


Fig. 532.

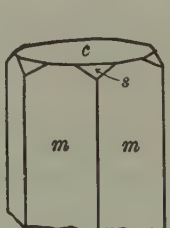


Fig. 533.

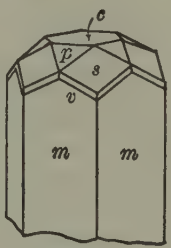


Fig. 534.

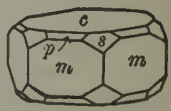


Fig. 535.

Figs. 532–535.—Beryl.

and is one of the few examples of the dihexagonal bipyramidal class. Axial ratio: $\dot{c} = 0.498$. Usual forms: $c\{0001\}$, $m\{10\bar{1}0\}$, $a\{11\bar{2}0\}$, $p\{10\bar{1}1\}$, $s\{11\bar{2}1\}$. Interfacial angles: $cp(0001 : 1011) = 29°\ 56\frac{1}{2}'$; $cs\{0001 : 11\bar{2}1\} = 44°\ 56'$; $ma(10\bar{1}0 : 11\bar{2}0) = 30°\ 0'$. The habit is usually prismatic (Figs. 532–534), but sometimes tabular (Fig. 535). Crystals are often very large.

H. = $7\frac{1}{2}$ to 8. **Sp. gr.** 2.7±.

Color, usually various tints of green, but sometimes white, yellow, pink, or blue.

Optical Properties. $n_\gamma(1.570) - n_\alpha(1.564) = 0.006$. Fragments are irregular with low first-order interference colors.

Chemical Composition. Beryllium aluminum metasilicate, $Be_3Al_2(SiO_3)_6$. The alkalies, sodium, lithium, and cæsium, often partly replace beryllium.

Blowpipe Tests. Fusible on thin edges (at 6). Insoluble in acids.

Distinguishing Features. Beryl is usually distinguished by crystal habit. It is harder than apatite and not as heavy as corundum.

Uses. The deep green variety, emerald, is a valuable gem. The best emeralds are found at Muzo in Colombia. Sea-green (aquamarine) and pink varieties are also used as gems.

Occurrence. 1. In granite pegmatites associated with topaz, albite, lepidolite, spodumene, etc. San Diego county, California.

2. In mica schists and gneisses. North Carolina.

3. In calcite veins in limestone. Muzo, Colombia.

Wollastonite, $CaSiO_3$

Form. Wollastonite is found in cleavable, columnar, fibrous, and compact masses. Euhedral crystals, which are rare, are monoclinic and are elongate in the direction of the *b*-axis.

Cleavage, in two directions (001 and 100) at angles of 84½°.

H. = 4½ to 5. **Sp. gr.** 2.8±.

Color, white or gray.

Optical Properties. $n_\gamma(1.633) - n_\alpha(1.621) = 0.012$. Fragments are acicular with bright interference colors, parallel extinction, and positive elongation.

Chemical Composition. Calcium metasilicate, $CaSiO_3$.

Blowpipe Tests. Fuses (at 4) to a white glass, giving a yellowish-red flame.

It is decomposed by HCl with the separation of powdery silica and usually effervesces because of admixed calcite.

Distinguishing Features. Wollastonite resembles tremolite

but differs in cleavage. It may be necessary to use optical tests to distinguish them.

Occurrence. 1. In crystalline limestones at the contact with igneous rocks, often associated with garnet, diopside, etc. Lewis county, New York.

2. In calcareous inclusions in volcanic rocks.

Spodumene, $LiAl(SiO_3)_2$

Form. Spodumene occurs in rough monoclinic crystals and in cleavable masses. The habit of the crystals is prismatic and usually tabular parallel to {100}.

Cleavage, in two directions at angles of 93° and 87°. There is also parting parallel to {100} at times, which causes the mineral to break into plates.

H. = 6½. **Sp. gr.** 3.1±.

Color, white, gray, colorless, lilac, greenish.

Optical Properties. $n_\gamma(1.67) - n_\alpha(1.65) = 0.02$. Fragments are prismatic with first-order interference colors and oblique extinction of 20° to 25°.

Chemical Composition. Lithium aluminum metasilicate, $LiAl(SiO_3)_2$. Sodium often replaces part of the lithium.

Blowpipe Tests. Fuses (at 3½) to a clear glass, giving a purple-red flame.

Insoluble in acids.

Distinguishing Features. Distinguished from feldspars by its higher specific gravity, and from tremolite by differences in cleavage.

Uses. Spodumene has been used to some extent as a source of lithium salts. A transparent lilac variety called *kunzite* is used as a gem and also a transparent emerald-green variety known as *hiddenite.*

Occurrence. 1. In granite pegmatites associated with albite, lepidolite, tourmaline, etc. Pennington county, South Dakota. One crystal from the Etta Mine in this county measured 14 meters in length.

GARNET GROUP $(Ca,Mg,Mn,Fe)_3(Al,Fe,Cr)_2(SiO_4)_3$

Grossularite,	$Ca_3Al_2(SiO_4)_3$
Almandite,	$Fe_3Al_2(SiO_4)_3$
Pyrope,	$Mg_3Al_2(SiO_4)_3$
Andradite,	$Ca_3Fe_2(SiO_4)_3$

Form. Garnet is found in distinct crystals, which are usually embedded, in granular or compact masses, and in the form of sand.

Garnet crystallizes in the hexoctahedral class of the isometric system. The usual forms are the dodecahedron $d\{110\}$ and the trapezohedron $n\{211\}$. The hexoctahedron $\{321\}$ is sometimes found, but the cube and octahedron are exceedingly rare forms for garnet. Figs. 536–539 illustrate commonly occurring garnet

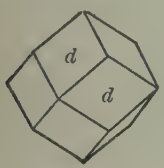


Fig. 536.

Fig. 537.

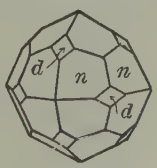


Fig. 538.

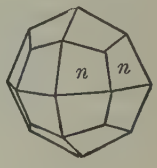


Fig. 539.

Figs. 536–539.—Garnet.

crystals ranging from dodecahedral habit to trapezohedral habit. Interfacial angles: $dd(110 : 101) = 60°$; $dd(110 : 1\bar{1}0) = 90°$, nn $(211 : 121) = 33° 33\frac{1}{2}'$; $nn(211 : 2\bar{1}1) = 48° 11\frac{1}{2}'$; $dn(110 : 211) = 30°$.

Cleavage. Usually absent, but some varieties show parting.

H. = 7. **Sp. gr.** varies from 3.5 to 4.2.

Color, various tints and shades of red, brown, yellow, green, and occasionally black.

Optical Properties. n varies from 1.74 to 1.88. Isotropic. Fragments are irregular, colorless or pale red, and dark between crossed nicols, but some varieties have weak double refraction.

Chemical Composition. The general formula of garnet is $(Ca,Mg,Mn,Fe)_3(Al,Fe,Cr)_2(SiO_4)_3$. The four most common minerals of the group are:

	n	Sp. gr.
Grossularite, $Ca_3Al_2(SiO_4)_3$	1.736 to 1.763	3.53 ±
Almandite $Fe_3Al_2(SiO_4)_3$	1.778 to 1.815	4.25 ±
Pyrope, $Mg_3Al_2(SiO_4)_3$	1.741 to 1.760	3.51 ±
Andradite, $Ca_3Fe_2(SiO_4)_3$	1.857 to 1.887	3.75 ±

Two other rare minerals of the group are also known, viz.; spessartite, $Mn_3Al_2(SiO_4)_3$, and uvarovite $Ca_3Cr_2(SiO_4)_3$.

It is rare to find a garnet that corresponds exactly to any one of these as can be seen from the following analyses:

Analyses of Garnets

	CaO	MgO	FeO	MnO	Al_2O_3	Fe_2O_3	Cr_2O_3	SiO_2
Grossularite	33.9	1.7	....	....	20.2	4.9	....	39.5
Pyrope	5.0	17.9	8.1	0.5	22.4	5.5	....	40.9
Almandite	1.4	3.6	33.8	1.1	22 7	....	....	37.6
Almandite	2.4	3.7	29.5	4.8	19.2	4.9	....	35.9
Spessartite	0.5	....	5.7	37.2	20.9	....	....	35.7
Andradite	31.5	tr.	0.3	....	2.2	30.4	.....	35.3
Uvarovite	31.6	1.5	....	.....	5.7	2.0	21.8	36.9

Blowpipe Tests. Fusible from 3 to 4.

Insoluble before fusion, but after fusion (alone, not with Na_2CO_3) it gelatinizes with HCl.

Distinguishing Features. Garnet is recognized by crystal habit, absence of cleavage, rather high specific gravity, and by its hardness.

Uses. Garnet is used as an abrasive, especially for finishing wood and leather. New York has furnished the total domestic supply. Spain has also produced abrasive garnet from alluvial deposits. Some varieties are used for gems.

Occurrence. 1. In crystalline limestones especially at contacts, associated with wollastonite, diopside, vesuvianite, etc. (grossularite and andradite).

2. In schists and gneisses (almandite).

3. In eclogites with pyroxenes or amphiboles.

4. In granites and granite pegmatites (almandite).
5. In peridotites and derived serpentines (pyrope).
6. In nepheline- and leucite-bearing lavas, such as phonolites, etc. (*melanite* variety of andradite).
7. In sands.

OLIVINE GROUP—ORTHORHOMBIC

The olivine group is a group of orthorhombic orthosilicate minerals with the general formula $R_2''SiO_4$ in which R'' may be Mg, Fe, or Mn. The minerals of this group are: forsterite, Mg_2SiO_4; fayalite, Fe_2SiO_4; olivine, $(Mg,Fe)_2SiO_4$; tephroite, Mn_2SiO_4; and monticellite, $CaMgSiO_4$. Olivine is an isomorphous mixture of magnesium and ferrous silicates, and monticellite, a double salt. Olivine is the only common mineral of the group.

The following analyses show the range in composition of these minerals:

	MgO	FeO	CaO	MnO	SiO_2	Misc.
Forsterite	54.4	1.5	0.8	....	42.8	ign. = 0.8
Olivine	50.3	8.5	....	....	41.2	
Olivine	44.1	17.5	....	....	39.2	
Olivine	30.6	28.1	1.4	1.2	38.9	
Fayalite	2.1	65.5	....	....	32.4	
Tephroite	1.4	1.1	1.0	65 6	30.2	ign. = 0.4; ZnO = 0.3
Monticellite	22.0	5.6	34.9	....	37.9	

OLIVINE, $(Mg,Fe)_2SiO_4$

Form. For olivine the characteristic occurrences are granular masses or disseminated crystals and grains. Crystals are orthorhombic and are usually tabular in habit. Figure 540 represents a crystal with all the seven type forms of the rhombic bipyramidal class. $a\{100\}$, $b\{010\}$, $c\{001\}$, $m\{110\}$, $d\{101\}$, $k\{021\}$, $p\{111\}$.

H. = 6½ to 7. **Sp. gr.** 3.3±.

Color, yellowish green to bottle green.

Optical Properties. $n_\gamma(1.699) - n_\alpha(1.662) = 0.037$. Fragments are irregular and colorless with bright interference colors.

Chemical Composition. Magnesium and iron orthosilicate $(Mg,Fe)_2SiO_4$, (FeO = 5.0 to 30.0 per cent.).

Blowpipe Tests. Infusible.

Gelatinizes with HCl.

Distinguishing Features. Olivine is usually recognized by its bottle-green color and absence of cleavage.

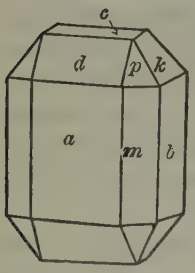


FIG. 540.—Olivine.

Uses. Clear transparent olivine is used as a gem under the name peridot.

Occurrence. 1. In peridotites with enstatite or diallage. The olivine is usually partially altered to serpentine. An igneous rock composed practically of olivine alone is called dunite.

2. In basalts, olivine diabases, and olivine gabbros as an essential constituent.

3. In tuffs and volcanic bombs.

4. In meteorites. Pallasite is a meteorite rock with olivine filling the cavities in a spongy mass of iron.

Forsterite, Mg_2SiO_4

Form. Forsterite usually occurs in disseminated anhedral or subhedral crystals. Euhedral, orthorhombic crystals like olivine in form and angles are known, but are rare.

H. = 6½. **Sp. gr.** 3.25±.

Color, gray to pale green or yellow.

Optical Properties. $n_\gamma(1.670) - n_\alpha(1.635) = 0.035$. (For pure artificial Mg_2SO_4). The indices of refraction of the natural mineral are a little higher on account of the presence of Fe_2SiO_4). Fragments are irregular with bright interference colors.

Chemical Composition. Magnesium orthosilicate Mg_2SiO_4 (MgO = 57.1, SiO_2 = 42.9), with a little ferrous iron replacing the magnesium. With increasing iron it grades into olivine.

Blowpipe Tests. Infusible before the blowpipe.

Soluble in HCl with gelatinization.

Distinguishing Features. It is distinguished from olivine by lower iron content and by lower indices of refraction. From other magnesium silicates it is distinguished by the absence of water.

Occurrence. 1. In crystalline limestones as the product of dedolomitization. A common associate is spinel. Bolton, Massachusetts.

2. In contact-metamorphic zones with magnetite. Phillipsburg, Montana.

Willemite, Zn_2SiO_4

Form. This mineral is usually crystalline massive or granular massive. Crystals are hexagonal and prismatic in habit with the hexagonal prism $\{11\bar{2}0\}$, and the rhombohedron $\{10\bar{1}1\}$.

H. = $5\frac{1}{2}$. **Sp. gr.** 4.1±.

Color, pale red, yellow to green.

Optical Properties. $n_\gamma(1.717) - n_\alpha(1.693) = 0.024$. Fragments are irregular with bright interference colors.

Chemical Composition. Zinc orthosilicate, Zn_2SiO_4; (Zn = 58.0 per cent.). Manganese often replaces part of the zinc.

Blowpipe Tests. Fusible (at $5\frac{1}{2}$) with difficulty. With cobalt nitrate solution on charcoal the assay turns blue and the sublimate on the coal, green. Willemite is distinguished from calamine by the absence of water in the closed tube.

Gives a fine jelly when the HCl solution is heated.

Uses. Willemite is a source of zinc white and also of spelter.

Distinguishing Features. Willemite is often distinguished by its association with franklinite (black) and zincite (red).

Occurrence. 1. In crystalline limestone intimately mixed with franklinite and zincite. It perhaps has been formed by the metamorphism of calamine present in the original sedimentary limestone. Franklin Furnace, New Jersey.

2. In the oxidized zone of zinc deposits. (Calamine, however, is much more common in the oxidized zone).

CALAMINE, $Zn_2(OH)_2SiO_3$

Form. Calamine occurs as drusy crystalline coatings, more rarely in botryoidal and stalactitic forms with a spherulitic structure, and also massive. Crystals are orthorhombic, pyramidal class. The habit is usually tabular parallel to {010} and the two ends of the crystal are differently terminated. Figure 541 represents a typical crystal. The usual forms are: $c\{001\}$, $b\{010\}$, $m\{110\}$, $i\{031\}$, $s\{101\}$, $t\{301\}$, $v\{12\bar{1}\}$. Interfacial angles: $ct(001:301) = 61° 20\frac{1}{2}'$; $cs(001:101) = 31° 23'$.

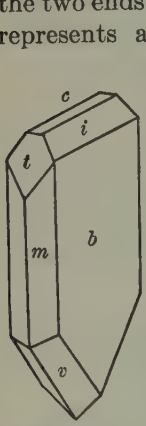


FIG. 541.—Calamine.

Cleavage, perfect parallel to the length of the crystal.

H. = 5. **Sp. gr.** 3.4±.

Color, colorless, white, and pale colors.

Optical Properties. $n_\gamma(1.64) - n_\alpha(1.61) = 0.03$. Fragments are irregular or prismatic with parallel extinction. Crystals have parallel extinction and positive elongation. The interference colors are bright.

Chemical Composition. Basic zinc metasilicate, $Zn_2(OH)_2SiO_3$ or $ZnSiO_3 \cdot Zn(OH)_2$; (Zn = 54.2 per cent., H_2O = 7.5 per cent.). The common impurities are iron and aluminum.

Blowpipe Tests. Fusible on the edges (at 5). In the closed tube decrepitates and gives off water. Heated with cobalt nitrate solution on charcoal, the assay becomes blue and the sublimate on the coal, green.

Soluble in HCl, giving a fine jelly on partial evaporation.

Distinguishing Features. Calamine resembles smithsonite and is often distinguished from it by the sharp, well-defined crystals, and by the cleavage parallel to the length of the crystals.

Uses. Calamine is one of the ores of zinc.

Occurrence. 1. A mineral characteristic of the oxidized zone, usually derived from sphalerite and often associated with smithsonite. Granby, Newton county, Missouri, is a prominent locality.

Scapolite, $m(3CaAl_2Si_2O_8 \cdot CaCO_3) + n(3NaAlSi_3O_8 \cdot NaCl)$.

Form. Scapolite occurs in rough crystals, in cleavable, columnar, and massive forms. Crystals are tetragonal (tetragonal bipyramidal class), prismatic in habit, and often resemble diopside crystals. The usual forms are: $a\{100\}$, $m\{110\}$, $r\{111\}$, and $\{101\}$. Interfacial angles : $rr(111 : \bar{1}11) = 43°\ 45'$, $mr(110:111) = 58°\ 12'$; $am(100:110) = 45°$. Figure 542 represents a typical scapolite crystal.

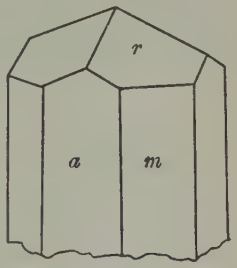


FIG. 542.—Scapolite.

Cleavage, imperfect parallel to $\{100\}$ and $\{110\}$, so in four directions in one zone at angles of 45°.

H. = 5½. **Sp. gr.** 2.56 to 2.77.

Color, white, gray, greenish, or reddish.

Optical Properties. $n_\gamma(1.595 \text{ to } 1.550) - n_\alpha(1.557 \text{ to } 1.542) = 0.038 \text{ to } 0.018$. Fragments are prismatic with parallel extinction, bright interference colors, and negative elongation.

Chemical Composition. An isomorphous mixture of calcium aluminum carbonate-silicate with sodium aluminum chlorid-silicate in varying proportions.

Blowpipe Tests. Easily fusible (at 3) to a white glass with intumescence coloring the flame yellow.

Partially decomposed by HCl. Some varieties give slight effervescence when acid is hot.

Distinguishing Features. Scapolite resembles diopside and the feldspars but is distinguished by its tetragonal crystals and by optical tests.

Occurrence. 1. In crystalline limestones at the contacts with igneous rocks and associated with diopside, garnet, and other silicates.

2. In gabbros along the border of apatite veins. Formed from plagioclase by the pneumatolytic process known as scapolitization.

Vesuvianite, $Ca_6Al_3(OH,F)(SiO_4)_5$

Form. For vesuvianite the characteristic form is striated columnar masses, but crystals belonging to the tetragonal system are also common. $\dot{c} = 0.537$. The usual forms are $m\{110\}$, $a\{100\}$, $c\{001\}$, $p\{111\}$, $t\{331\}$, $s\{311\}$. The interfacial angles are: $cp(001 : 111) = 37°\ 13\frac{1}{2}'$; $ap(100 : 111) = 64°\ 40\frac{1}{2}'$; $pp(111 : 1\bar{1}1) = 50°\ 39'$; $mt(110 : 331) = 23°\ 41\frac{1}{2}'$; $as(100 : 311) = 35°\ 10'$; $am(100 : 110) = 45°\ 0'$. The habit is

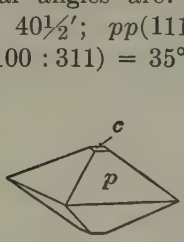


Fig. 543.

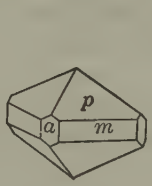


Fig. 544.

Fig. 545.

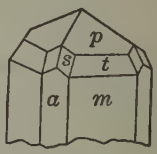


Fig. 546.

Figs. 543–546.—Vesuvianite.

prismatic or low pyramidal and the cross-section is usually square or octagonal. Figs. 543–546 are drawings of typical vesuvianite crystals.

H. = $6\frac{1}{2}$. **Sp. gr.** $3.4\pm$.

Color, yellow, brown, or green.

Optical Properties. $n_\gamma(1.723) - n_\alpha(1.722) = 0.001$. Fragments are irregular with anomalous interference colors.

The weak double refraction may be proved by means of a gypsum plate.

Chemical Composition. Basic calcium aluminum orthosilicate, probably $Ca_6Al_3(OH,F)(SiO_4)_5$. Iron replaces part of the aluminum and magnesium, part of the calcium. Boron is found in some varieties.

Blowpipe Tests. Fuses (at 3) with intumescence to a colored

glass. In the closed tube at a high temperature it gives a little water (about 2 per cent.).

Slightly decomposed by HCl. After fusion (alone, not with Na_2CO_3) it gelatinizes with HCl.

Distinguishing Features. Vesuvianite is distinguished from most other minerals by its crystal form. In massive specimens the weak double refraction with peculiar interference colors is the best test to apply.

Uses. Californite, a massive jade-like variety, is used as a semi-precious stone. It occurs in Siskiyou and Fresno counties, California.

Occurrence. 1. In crystalline limestones at the contacts with igneous rocks, and associated with garnet, diopside, wollastonite, etc. Crestmore, California.

2. In calcareous inclusions in volcanic rocks. Vesuvius.

Zircon, $ZrSiO_4$

Form. Zircon is practically always found in crystals which are either embedded or occur loose in sands.

Zircon is one of the best examples of the ditetragonal bipyramidal class of the tetragonal system. $\dot{c} = 0.640$. Usual forms: $m\{110\}$, $a\{100\}$, $p\{111\}$, $u\{331\}$, $x\{131\}$. Interfacial angles: $pp(111 : \bar{1}11) = 56° 40'$; $mp(110 : 111) = 47° 50'$; $ap(100 : 111) = 61° 40'$; $mu(110 : 331) = 20° 12'$. The habit is low pyramidal or prismatic (Figs. 547 to 550).

H. = 7½. **Sp. gr.** 4.7±.

Color, usually brown but also red, yellow, and colorless. Luster, adamantine.

Optical Properties. $n_\gamma(1.993) - n_\alpha(1.931) = 0.062$. Fragments are irregular with fourth-order interference colors.

Chemical Composition. Zirconium orthosilicate, $ZrSiO_4$.

Blowpipe Tests. Infusible, but loses color.

Practically insoluble in acids.

Distinguishing Features. Zircon is easily distinguished by its crystal form and high specific gravity.

Uses. Certain kinds of zircon called hyacinth are used as gems. It is one of the few minerals that rivals the diamond in brilliance and "fire." Zircon is the source of zirconia (ZrO_2) used as a glower in the Nernst lamp.

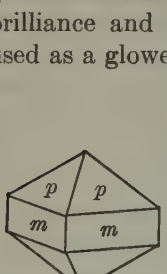


Fig. 547.

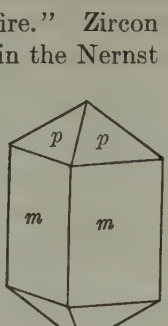


Fig. 548.

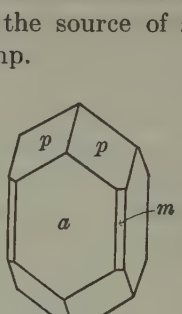


Fig. 549.

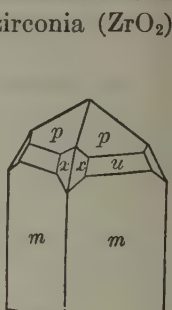


Fig. 550.

Figs. 547–550.—Zircon.

Occurrence. 1. As an accessory mineral in igneous rocks, especially the "acid" rocks rich in soda such as syenites and soda granites. El Paso county, Colorado.

2. As a constituent of sands and gravels. Ceylon.

Topaz, $Al_2(F,OH)_2SiO_4$

Form. Topaz occurs in well-defined crystals and in cleavable masses. It crystallizes in the bipyramidal class of the orthorhombic system. $\dot{a} : \bar{b} : \dot{c} = 0.528 :: 0.477$. Usual forms: $m\{110\}$, $l\{120\}$, $c\{001\}$, $f\{021\}$, $y\{041\}$, $u\{111\}$, $o\{221\}$, $i\{223\}$. Interfacial angles: $mm(110 : 1\bar{1}0) = 55°\ 43'$; $ll(120 : \bar{1}20) = 86°\ 49'$; $ml(110 : 120) = 19°\ 44'$; $ff(021 : 0\bar{2}1) = 87°\ 18'$; $yy(041 : 0\bar{4}1) = 124°\ 42'$; $ci(001 : 223) = 34°\ 14'$; $cu(001 : 111) = 45°\ 35'$; $co(\bar{0}01 : 221) = 63°\ 54'$. The habit is usually prismatic, with $m\{110\}$ and $l\{120\}$ about equally developed. Figures 551–554 represent typical crystals.

Cleavage, perfect in one direction parallel to $\{001\}$.

H. = 8. **Sp. gr.** 3.5±.

Color, colorless, white, yellowish, bluish, reddish.

Optical Properties. $n_\gamma(1.622) - n_\alpha(1.613) = 0.009$. Frag-

ments are plates with irregular outline and low first order interference colors. Cleavage flakes give a positive biaxial interference figure. The optical orientation of topaz is $\alpha = a$, $\beta = b$, $\gamma = c$; hence (010) is the axial plane.

Chemical Composition. Aluminum fluo-silicate, $Al_2(F, OH)_2SiO_4$. Hydroxyl replaces part of the fluorin.

Blowpipe Tests. Infusible. Heated with cobalt nitrate solution it gives a deep blue color. On intense ignition in a closed tube some varieties give a little water. On heating with $NaPO_3$ in the closed tube it etches the tube.

Partially decomposed by H_2SO_4.

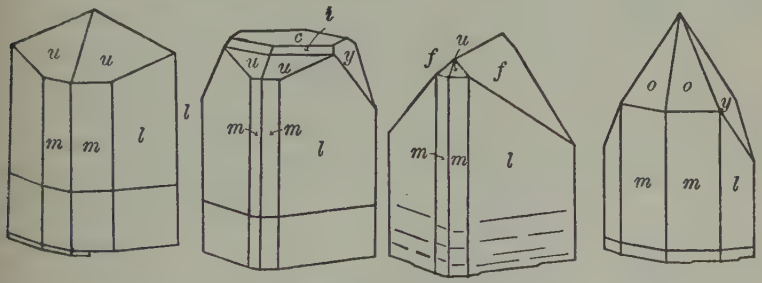


FIG. 551. FIG. 552. FIG. 553. FIG. 554.

FIGS. 551–554.—Topaz.

Distinguishing Features. Topaz is characterized by its perfect cleavage in one direction, high specific gravity, and great hardness.

Uses. Topaz is sometimes used as a gem. Many of the stones that pass for topaz are really yellow quartz (citrine).

Occurrence. 1. In granite pegmatites and surrounding rocks associated with tourmaline, lepidolite, albite, fluorite, apatite, beryl, etc. El Paso county, Colorado.

2. In cavities in rhyolites. Thomas Range, Juab county, Utah.

Andalusite, Al_2SiO_5

Form. Andalusite occurs in rough, attached or embedded crystals, in columnar masses, and in rolled pebbles. The crystals

are orthorhombic and prismatic in habit; the only common forms are {110} and {001} with a prism angle of 89° 12′ (110 : $1\bar{1}0$). (Fig. 555).

H. = 7½. (May appear softer on account of alteration.)

Sp. gr. 3.18±.

Color, usually gray, often with symmetrically arranged white or black areas. This variety is known as *chiastolite.* (See Fig. 555.)

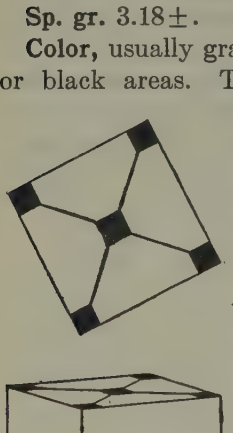


Fig. 555.—Andalusite (chiastolite).

Optical Properties. $n_\gamma(1.64) - n_\alpha(1.63) = 0.01$. Fragments are irregular, or prismatic with parallel extinction, and colorless or pleochroic from reddish to greenish. The interference colors are low first-order.

Chemical Composition. Aluminum silicate, Al_2SiO_5, or $Al_2O_3 \cdot SiO_2$, with the same composition as sillimanite and kyanite.

Blowpipe Tests. Infusible. It turns blue when heated with cobalt nitrate solution.

Insoluble in acids.

Distinguishing Features. The square prismatic crystals and symmetrical arranged inclusions are characteristic.

Uses. Some varieties have been used as gems. Chiastolite is sometimes used as a watch charm.

Occurrence. 1. In schists and slates as a product of contact or regional metamorphism. It is usually altered to a soft, fine grained sericitic aggregate. Lancaster, Massachusetts.

2. In granite pegmatites. San Diego County, California.

Kyanite, Al_2SiO_5

Form. For kyanite the characteristic form is bladed crystal or crystal aggregates. Crystals are triclinic, tabular parallel to {100}, and elongated in the direction of the *c*-axis.

Cleavage, perfect in one direction parallel to {100}. There are also imperfect cleavages in other directions.

H. = 4½ (parallel to the length) and 7 (perpendicular to the length). **Sp. gr.** 3.60±.

Color, blue, bluish-gray, green, or white, often colored in spots and streaks.

Optical Properties. $n_\gamma(1.728) - n_\alpha(1.712) = 0.016$. Fragments are prismatic or acicular with oblique extinction of 30° and bright interference colors. Cleavage flakes give a biaxial interference figure with the axial plane oblique to the edge.

Chemical Composition. Aluminum silicate, Al_2SiO_5 or $Al_2O_3 \cdot SiO_2$. Sillimanite, andalusite, and kyanite all have the same composition, but differ in physical properties.

Blowpipe Tests. Infusible. It turns blue when heated with cobalt nitrate solution.

Insoluble in acids.

Distinguishing Features. The bladed structure and variation of hardness with direction are characteristic.

Occurrence. 1. In schists and gneisses as the product of regional metamorphism. It is often associated with staurolite and garnet. Lincoln county, North Carolina.

Sillimanite, Al_2SiO_5

Form. Sillimanite occurs in prismatic and acicular crystals and in fibrous masses. It crystallizes in the orthorhombic system, but distinct crystals are rare. The prism faces with ($110 : 1\bar{1}0 = 88°$) are usually the only forms present.

Cleavage, perfect in one direction parallel to {010}.

H. = 6½. (Fibers may appear to be lower). **Sp. gr.** 3.23±.

Color, brown, gray, or white.

Optical Properties. $n_\gamma(1.681) - n_\alpha(1.660) = 0.021$. Fragments are prismatic or acicular with parallel extinction and positive elongation. The interference colors are bright.

Chemical Composition. Aluminum silicate, Al_2SiO_5 or $Al_2O_3 \cdot SiO_2$, with the same composition as andalusite and kyanite.

Blowpipe Tests. Infusible. It turns blue when heated with cobalt nitrate solution.

Insoluble in acids.

Distinguishing Features. Sillimanite may be distinguished from similar minerals by optical tests.

Uses. Jade-like varieties were used for implements by prehistoric man in Europe. The artificial mineral is now a commercial product.

Occurrence. 1. In gneisses and schists, as the result of metamorphism. Norwich, Connecticut.

EPIDOTE GROUP—MONOCLINIC

The epidote group is a group of basic orthosilicates of calcium and aluminum, with essentially the general formula $(Ca,Fe'')_2(Al,Fe''',Mn''',Ce,Cr''')_3(OH)(SiO_4)_3$. The only pure compound is the mineral (clinozoisite) fouquéite with the formula $Ca_2Al_3(OH)(SiO_4)_3$. Epidote is an isomorphous mixture of this compound with $Ca_2Fe_3(OH)(SiO_4)_3$, a possible mineral yet to be discovered. Piedmontite is a manganiferous epidote and allanite, a cerium-bearing epidote.

EPIDOTE, $Ca_2(Al,Fe)_3(OH)(SiO_4)_3$

Form. In crystals, in columnar aggregates, and in granular masses. The crystals are monoclinic, prismatic in habit, and are elongated in the direction of the *b*-axis instead of the *c*-axis, as in most monoclinic minerals. Usual forms: $a\{100\}$, $b\{010\}$, $c\{001\}$, $u\{120\}$, $r\{\bar{1}01\}$, $n\{\bar{1}11\}$. Interfacial angles: $ac(100:001) = 64°\ 37'$; $cr(001:\bar{1}01) = 63°\ 42'$; $nn(\bar{1}11:\bar{1}1\bar{1}) = 70°\ 29'$. $au(100:210) = 35°\ 29\frac{1}{2}'$. Figure 556 is an end-view of a typical crystal, and Fig. 557, the end-view of a twin-crystal with $a\{100\}$ as twin plane.

Cleavage, {001} perfect; {100} imperfect.

H. = $6\frac{1}{2}$. **Sp. gr.** 3.4–3.5.

Color, usually pistache-green, but varies from pale yellowish-green to deep brownish-green and almost black, according to the amount of iron present.

Optical Properties. $n_\gamma(1.767) - n_\alpha(1.730) = 0.037$. Fragments are irregular or prismatic with parallel extinction and show third-to fourth-order bright interference colors. The deep colored varieties are pleochroic from colorless to pale green. Cleavage flakes give an interference figure consisting of an axial bar with concentric rings.

Chemical Composition. Basic calcium aluminum and iron orthosilicate, $Ca_2(Al,Fe)_3(OH)(SiO_4)_3$, an isomorphous mixture

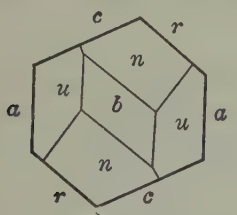


FIG. 556.

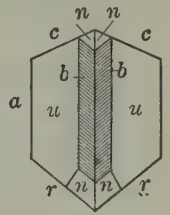


FIG. 557.

FIGS. 556, 557.—Epidote.

of $Ca_2Al_3(OH)(SiO_4)_3$ (clinozoisite) and $Ca_2Fe_3(OH)(SiO_4)_3$, unknown. Ferrous iron may replace part of the calcium. The following analyses illustrate the isomorphism.

	CaO	FeO	Al_2O_3	Fe_2O_3	SiO_2	H_2O	
Clinozoisite.....	24.4	0.8	31.9	3.0	37.8	2.2	MnO = trace
Epidote.....	23.8	0.5	29.5	5.7	38.0	2.0	MnO = 0.2
Epidote.....	23.9	...	26.5	8.2	39.2	2.2	
Epidote.....	23.3	0.9	22.6	14.0	37.8	2.1	

Blowpipe Tests. Fusible (at 3) to a colored glass with intumescence. In the closed tube at a high temperature it gives a little water (about 2 per cent.).

Partially decomposed by HCl. After fusion (alone, not with Na_2CO_3) it gelatinizes with HCl.

Distinguishing Features. Epidote can usually be recognized by its peculiar green color. From clinozoisite it is distinguished by its higher indices of refraction, higher birefringence, and darker color.

Occurrence. 1. At the contact between igneous rocks, especially granites and limestones often associated with copper minerals.

2. As a product of hydrothermal alteration in various kinds of rocks.

3. In schists, especially as the product of intense folding, associated with hornblende. New York City.

Clinozoisite $Ca_2Al(OH)(SiO_4)_3$.

Form. In monoclinic crystals, prismatic in the direction of the *b*-axis, and in columnar and granular aggregates. The angles are like those of epidote with which clinozoisite is isomorphous. It is dimorphous with orthorhombic zoisite.

Cleavage, {001} perfect; {100} imperfect.

H. = 6½. **Sp. gr.** 3.3–3.4.

Color, gray to green.

Optical Properties. $n_\gamma(1.72) - n_\alpha(1.71) = 0.01$. Fragments are irregular or prismatic with parallel extinction. Pleochroism not noticeable in fragments or thin sections. The interference colors are upper first or lower second order and are somewhat anomalous.

Chemical Composition. Basic calcium aluminum orthosilicate, $Ca_2Al(OH)(SiO_4)_3$,(H_2O = 2.0). A little ferric iron replaces the aluminum. Sometimes ferrous iron is present.

Blowpipe Tests. Fusible (at 3) to a brown glass with intumescence. In the closed tube it gives a little water at a high temperature.

Partially decomposed by HCl, but after fusion (alone) it gelatinizes with HCl.

Distinguishing Features. It is distinguished from epidote by its paler color, which is due to the fact that it contains less iron.

Occurrence. 1. As a product of hydrothermal alteration in various kinds of rocks. It is sometimes associated with ores.

Prehnite, $H_2Ca_2Al_2(SiO_4)_3$

Form. Prehnite is found in crystalline druses and seams. Distinct crystals (orthorhombic) are very rare. The imperfect crystals are usually grouped in mammillary and globular forms, showing a series of ridges.

H. = 6 to 6½. **Sp. gr.** 2.9±.

Color, usually pale green or white.

Optical Properties. $n_\gamma(1.649) - n_\alpha(1.616) = 0.033$. Fragments are irregular with bright interference colors.

Chemical Composition. Acid calcium aluminum orthosilicate, $H_2Ca_2Al_2(SiO_4)_3$; (H_2O = 4.4 per cent.).

Blowpipe Tests. Easily fusible (at 2) with intumescence to a white glass. In the closed tube it gives water.

Decomposed by HCl and after fusion (alone, not with Na_2CO_3) it gelatinizes with HCl.

Distinguishing Features. Prehnite often resembles calamine, but is distinguished by its lower specific gravity and by its associates.

Occurrence. 1. A secondary mineral in cavities of diabases and basalts associated with datolite, pectolite, apophyllite, calcite, and the zeolites. Paterson, New Jersey.

Staurolite, $FeAl_5(OH)(SiO_6)_2$

Form. Staurolite crystallizes in the orthorhombic system and is rarely found massive. The habit is prismatic with the forms $c\{001\}$, $m\{110\}$, $b\{010\}$, and $r\{101\}$ (Fig. 558). Interfacial

angles : $mm(110 : 1\bar{1}0) = 50°\ 40'$; $cr(001 : 101) = 55°\ 16'$. Cruciform penetration twins with {032} as twin-plane are common.

H. = 7 to 7½. **Sp. gr.** 3.7±.

Color, brown.

Optical Properties. $n_\gamma(1.746) - n_\alpha(1.736) = 0.010$. Fragments are irregular with upper first-order interference colors and are pleochroic from light to deep yellow.

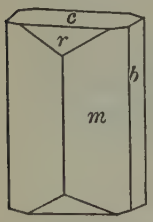


FIG. 558.—Staurolite.

Chemical Composition. Basic iron aluminum silicate, $FeAl_5(OH)(SiO_6)_2$, corresponding to the acid $H_8SiO_6(H_4SiO_4 + 2H_2O)$. The ferrous iron is partly replaced by magnesium, and the aluminum by ferric iron.

Distinguishing Features. The crystal form of staurolite is distinctive together with its dark brown color and its occurrence in schists.

Blowpipe Tests. Infusible.

Partially decomposed by H_2SO_4.

Occurrence. 1. In mica schists often associated with kyanite, sillimanite, and garnet. Fannin county, Georgia.

TOURMALINE, $R_9Al_3B_2(OH)_2Si_4O_{19}$

Form. Tourmaline usually occurs in distinct, attached or embedded crystals, and in columnar subradiating aggregates. Tourmaline is the type example of the ditrigonal pyramidal class of the hexagonal system. $\dot{c} = 0.447$. Usual forms: $a\{11\bar{2}0\}$, $m\{10\bar{1}0\}$, $m_1\{01\bar{1}0\}$, $r\{10\bar{1}1\}$, $e\{01\bar{1}2\}$, $o\{02\bar{2}1\}$, $c\{0001\}$, $t\}21\bar{3}1\}$, $u\{32\bar{5}1\}$, $x\{12\bar{3}2\}$, $r_1\{01\bar{1}1\}$, $e_1\{10\bar{1}2\}$, $c_1\{000\bar{1}\}$. Interfacial angles: $rm(10\bar{1}1 : 10\bar{1}0) = 27°\ 20'$; $em_1(01\bar{1}2 : 01\bar{1}0) = 75°\ 30\frac{1}{2}'$; $om_1(02\bar{2}1 : 01\bar{1}0) = 44°\ 3'$; $ee(01\bar{1}2 : \bar{1}012) = 25°\ 2'$; $rr(10\bar{1}1 : \bar{1}101) = 46°\ 52'$; $oo(02\bar{2}1 : \bar{2}021) = 77°\ 0'$; $xx(12\bar{3}2 : \bar{1}3\bar{2}2) = 21°\ 18'$; $xx(12\bar{3}2 : 3\bar{2}12) = 43°\ 22\frac{1}{2}'$; $tt(21\bar{3}1 : \bar{2}3\bar{1}1) = 63°\ 48'$; $tt(21\bar{3}1 : 3\bar{1}\bar{2}1) = 30°\ 38\frac{1}{2}'$, $am(11\bar{2}0 : 10\bar{1}0) = 30°\ 0'$; $aa(11\bar{2}0 : 2\bar{1}\bar{1}0) = 60°\ 0'$.

The habit is short to long prismatic and the cross-section three-, six-, or nine-sided, very often being rounded triangular

like a spherical triangle. The two ends of the crystals are usually terminated differently. Figures 559 to 562 represent typical tourmaline crystals.

Cleavage, none.

H. = 7 to 7½. **Sp. gr.** 3.00 to 3.25.

Color, usually black, but also brown, green, blue, red, and pink, rarely colorless. The exterior and interior and also the opposite ends of a crystal often differ in color. Transparent colored crystals show pleochroism with a dichroscope.

Tourmaline is pyroelectric; that is, a crystal which has been heated will on cooling develop positive electricity at one end and negative electricity at the other. This may be tested with a fine hair.

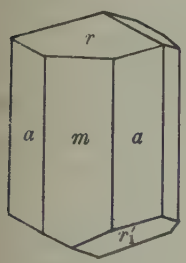


Fig. 559.

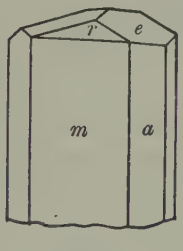


Fig. 560.

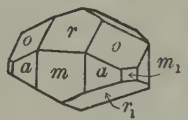


Fig. 561.

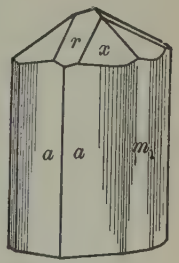


Fig. 562.

Figs. 559–562.—Tourmaline.

Optical Properties. $n_\gamma(1.653) - n_\alpha(1.631) = 0.022$. Fragments are irregular or prismatic with parallel extinction. The interference colors are bright. The black and deep colored varieties are pleochroic (often from blue to smoke-colored), while the light colored varieties are colorless, but in thick fragments or small crystals are also pleochroic.

Chemical Composition. A complex borosilicate of aluminum, iron, magnesium, and the alkalies. No satisfactory formula has yet been established. Penfield gives $R_9^1Al_3B_2(OH)_2Si_4O_{19}$, in which R^1 is iron, magnesium, and the alkalies. The following are typical analyses:

Analyses of Tourmaline

	Li_2O	Na_2O	H_2O	FeO	MgO	Al_2O_3	B_2O_3	SiO_2	Misc.
1. Pink	1.9	2.1	3.4	0.2	....	42.2	10.6	37.6	2.0
2. Pale green	1.3	2.2	3.3	1.5	....	41.3	10.6	36.7	3.8
3. Brown	tr	0.9	3.1	0.9	14.6	28.5	10.4	35.3	Ca = 5.1
4. Black	tr	2.2	3.6	11.9	4.5	31.1	9.9	34.9	2.2
5. Black	tr	2.0	3.6	14.2	1.0	33.9	9.6	35.0	0.6

Three principal varieties based upon composition and color are recognized viz., (1) iron tourmaline, black (analyses 4 and 5), (2) magnesium tourmaline, brown (analysis 3), (3) alkali tourmaline, red, green, or blue (analyses 1 and 2).

Blowpipe Tests. The fusibility varies from easy fusibility at 3 (magnesium variety) to infusibility (alkali variety). In the closed tube at a very high temperature gives water (from 2 to 4 per cent.). It gives a momentary green flame when fused with boric acid flux. ($3KHSO_4 + CaF_2$).

Insoluble in acids. After fusion (alone, not with Na_2CO_3) it gelatinizes with HCl.

Distinguishing Features. The triangular cross-section is characteristic of tourmaline. The black or common variety of tourmaline is distinguished from hornblende by the cross-section and by the absence of cleavage.

Uses. The transparent red and green varieties of tourmaline are used as gems.

Occurrence. 1. In granite pegmatites often associated with albite, lepidolite, beryl, apatite, fluorite. Pala, San Diego county, California.

2. In rocks surrounding granite pegmatites often associated with cassiterite, topaz, etc. Greisen is a quartz-muscovite rock formed from granite by pneumatolysis; luxullianite, a variety of quartz porphyry in which the quartz is partly replaced by tourmaline. Cornwall, England.

3. In crystalline limestones (the brown magnesium variety),

associated with spinel, phlogopite, corundum, etc. Hamburg, New Jersey.

4. In high-temperature veins with copper and lead minerals. Meadow Lake, Nevada county, California.

Datolite, $CaB(OH)SiO_4$

Form. Datolite occurs in crystals, crystalline druses, and crystalline masses. Crystals are monoclinic and are usually complex and difficult to decipher. As the angle β (the acute angle between the a and c-axes) is 89° 51′, the crystals often appear to be orthorhombic. Figure 563 is an orthographic projection of a datolite crystal with the forms: $m\{110\}$, $x\{102\}$, $n\{111\}$, $a\{100\}$, $\epsilon\{\bar{1}12\}$, $\lambda\{\bar{1}13\}$ and $\mu\{\bar{1}14\}$.

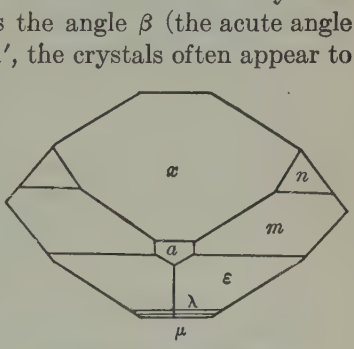


Fig. 563.—Datolite.

H. = 5½. **Sp. gr.** 2.9±.

Color, colorless, white, pale green.

Optical Properties. $n_\gamma(1.670) - n_\alpha(1.626) = 0.044$. Fragments are irregular with bright interference colors.

Chemical Composition. Basic calcium boron orthosilicate, $CaB(OH)SiO_4$; (H_2O = 5.6 per cent.).

Blowpipe Tests. Easily fusible (at 2) with intumescence to a glass, coloring the flame green. In the closed tube it gives water. Gelatinizes with HCl.

Distinguishing Features. Datolite is usually recognized by the complex crystals without cleavage and by its occurrence in cavities of igneous rocks with the zeolites.

Occurrence. 1. Found in cavities of diabases and basalts associated with the zeolites, apophyllite, prehnite, pectolite [$HNaCa_2(SiO_3)_3$], etc.

Axinite, $HCa_2(Fe,Mn)Al_2B(SiO_4)_4$

Form. Axinite occurs in crystals and crystalline aggregates. The crystals furnish one of the best examples of the triclinic

system. The habit is usually tabular and the cross-sections wedge-shaped. Figure 564 represents a typical crystal.

H. = 6½ to 7. **Sp. gr.** 3.3±.

Color, violet, brown, smoky gray.

Optical Properties. $n_\gamma(1.68) - n_\alpha(1.67) = 0.01$. Fragments are irregular with upper first-order interference colors. Thick fragments are pleochroic.

Chemical Composition. An acid calcium iron-manganese aluminum boron silicate, $HCa_2(Fe,Mn)Al_2B(SiO_4)_4$.

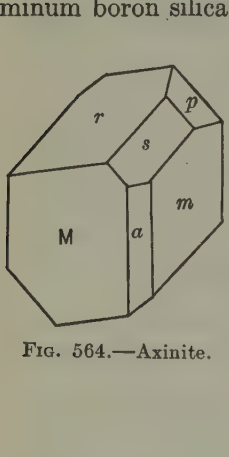


FIG. 564.—Axinite.

Blowpipe Tests. Easily fusible (at 2½) with intumescence to a dark glass. In the closed tube at a high temperature it gives a little water. When fused with $KHSO_4$ and CaF_2 it gives a green flame.

Insoluble in HCl. Gelatinizes after fusion.

Distinguishing Features. The acute-angled triclinic crystals are characteristic.

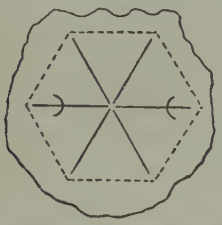
Occurrence. 1. At the contact of granites with basic lime-rich rocks such as schists and impure limestones.

MICA GROUP

The micas are acid orthosilicates of aluminum with magnesium, ferrous iron, and the alkalies. When heated to a high temperature they give from 2 to 5 per cent. of water.

The micas are monoclinic, but pseudohexagonal in habit. Distinct terminated crystals are very rare. The very perfect cleavage parallel to {001} is the most striking feature of the micas. They are optically biaxial with varying axial angle. In the absence of crystal faces, cleavage plates of the micas may be oriented by means of the percussion figure in connection with the interference figure. A sharp, quick blow with a dull conical point develops a six-rayed star. If the interference figure lies along one of the rays then that ray is the direction of the *b*-axis.

These are *micas of the first class* and are represented by Fig. 565. If the interference figure lies between two rays of the percussion figure, then the third ray is the direction of the *b*-axis. These are *micas of the second class* and are represented by Fig. 566. Muscovite and lepidolite are micas of the first class, while biotite and phlogopite are micas of the second class.



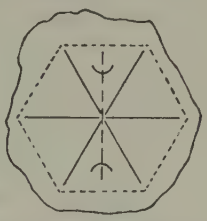


FIG. 565.—Mica of the first class. FIG. 566.—Mica of the second class.

MUSCOVITE, $H_2KAl_3(SiO_4)_3$

Form. Muscovite usually occurs in cleavages and scaly masses and but rarely in well-defined crystals. The crystals are tabular in habit, and pseudohexagonal or pseudorhombic, but are really monoclinic. Figure 567 represents a muscovite crystal in plan and side elevation. The side elevation proves it to be monoclinic.

Cleavage, very perfect in one direction parallel to {001}.

H. = 2½. **Sp. gr.** 2.83±.

Color, in thick sheets various tints of green, yellow, brown, and red. Thin sheets are colorless and transparent.

Optical Properties. $n_\gamma(1.597) - n_\alpha(1.560) = 0.037$. Cleavage flakes give low first-order interference colors ($n_\beta - n_\alpha = .004$) and in convergent light, a fine negative biaxial interference figure with large axial angle (2E = 60° to 75°). $\dot{a} = \beta$; $\dot{b} = \gamma$; $\dot{c}:\alpha = 1°$.

Chemical Composition. An acid potassium aluminum orthosilicate, $H_2KAl_3(SiO_4)_3$; (H_2O = 4.5 per cent.). The potassium is partially replaced by sodium. Some varieties contain an excess of silica over that required by the formula.

Blowpipe Tests. Fusible on thin edges (at 5) and whitens. In the closed tube it gives a little water.

Insoluble in acids and not decomposed by hot concentrated H_2SO_4.

Distinguishing Features. Muscovite is easily recognized by its elastic cleavage, and flakes with perfect cleavage in one direction. Pink muscovite is distinguished from lepidolite by the easy fusibility of the latter.

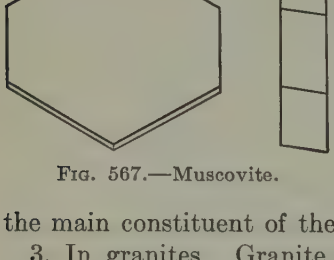


FIG. 567.—Muscovite.

Uses. Muscovite is used principally as an insulator for electrical apparatus, but has numerous other uses. India is the principal producer of muscovite.

Occurrence. 1. In granite pegmatites and granite aplites.

2. In schists and gneisses, often the main constituent of the mica schists.

3. In granites. Granite is about the only igneous rock in which muscovite occurs as an original constituent.

4. In sandstones and sands as a detrital mineral.

Sericite, $H_2KAl_3(SiO_4)_3$

Form. Sericite is probably dimorphous with muscovite. It occurs in scaly masses and very rarely is distinct crystals which are like muscovite in form and habit but very minute.

Cleavage, perhaps in one direction.

H. = 1½ to 2. **Sp. gr.** 2.8±.

Color, white, gray, or pale green.

Optical Properties. The optical constants are near those for muscovite, $n_\gamma(1.597) - n_\alpha(1.560) = 0.037$. Fragments are cleavage flakes or shreds with low first-order interference colors. The shreds show change of relief when examined in clove oil under the microscope in polarized light (use lower Nicol only).

Chemical Composition. Acid potassium aluminum orthosilicate; formula probably the same as muscovite, $H_2KAl(SiO_4)_3$.

(H_2O = 4.5 per cent.). The potassium is partially replaced by sodium.

Blowpipe Tests. Fusible on thin edges (at 5). In the closed tube it yields water.

Insoluble in acids.

Distinguishing Features. Sericite is recognized by its peculiar silky luster. It is usually called talc by miners.

Uses. It is a possible source of potassium salts. Extensive deposits of sericite schists are found in Georgia.

Occurrence. 1. As a product of hydrothermal alteration in ore deposits. It is, according to the researches of the author, a comparatively late mineral formed after the hypogene sulfids.

2. In schists and gneisses forming the sericite schists and sericite gneisses.

Lepidolite, $LiKAl_2(OH,F)(SiO_3)_3$

Form. Lepidolite usually occurs in scaly masses, rarely in crystals. Crystals are pseudohexagonal like those of muscovite, but are much smaller.

Cleavage, very perfect in one direction (parallel to 001).

H. = 2½ to 3½. **Sp. gr.** 2.84±.

Color, pale to deep lilac.

Optical Properties. $n_\gamma(1.605) - n_\alpha(1.560) = 0.045$. Cleavage flakes give low first-order interference colors, and in convergent light a negative, biaxial interference figure with large axial angle (2E = 60° to 80°).

Chemical Composition. Lithium, potassium aluminum fluosilicate, $LiKAl_2(OH,F)(SiO_3)_3$.

Blowpipe Tests. Easily fusible (at 2) with intumescence to a white glass, coloring the flame purple. In the closed tube on intense ignition it gives water which has an acid reaction due to the HF formed.

Partially decomposed by HCl. After fusion (alone, not with Na_2CO_3) it gelatinizes with HCl.

Distinguishing Features. Lepidolite is usually recognized by its lilac color and micaceous character. It is distinguished from the other micas by its easy fusibility and by the lithium flame.

Uses. Lepidolite is a source of lithium salts.

Occurrence. 1. In granite pegmatites and surrounding granites associated with tourmaline, albite, muscovite, spodumene, amblygonite, etc. Pala, San Diego county, California.

BIOTITE, $(H,K)_2(Mg,Fe)Al_2(SiO_4)_3$

Form. Biotite occurs in embedded crystals, in disseminated scales, and in lamellar masses. Crystals are pseudohexagonal like those of muscovite.

Cleavage, very perfect in one direction (parallel to 001).

H. = 2½ to 3. **Sp. gr.** 2.90±.

Color, black or dark brown. Thin sheets are translucent.

Optical Properties. $n_\gamma(1.638) - n_\alpha(1.579) = 0.044$. Cleavage flakes are almost dark between crossed nicols and in convergent light give a negative biaxial interference figure with a small axial angle (2E=0–20°) which is sometimes practically uniaxial.

Chemical Composition. Acid potassium magnesium and iron aluminum orthoclase, $(H,K)_2(Mg,Fe)_2Al_2(SiO_4)_3$. Ferric iron replaces part of the aluminum.

Blowpipe Tests. Fusible on edges (at 5) and turns white. In the closed tube it gives a little water (2 to 4 per cent.) on intense ignition.

Decomposed by hot concentrated H_2SO_4.

Distinguishing Features. Biotite is distinguished from the other micas by its dark color.

Occurrence. 1. In many kinds of igneous rocks, but especially prominent in granites, and also in certain dike rocks known as lamprophyres.

2. In schists and gneisses, sometimes as the dominant mineral, and often associated with muscovite.

3. In high-temperature veins.

Phlogopite, $H_2KMg_3Al(SiO_4)_3$

Form. Like the other micas, phlogopite occurs in crystals, in disseminated scales, and in lamellar masses. The crystals are pseudohexagonal, but are often prismatic in habit as well as tabular.

Cleavage, very perfect in one direction.

H. = 2½ to 3. **Sp. gr.** 2.80±.

Color, varies from pale brown to dark brown.

Optical Properties. $n_\gamma(1.606) - n_\alpha(1.562) = 0.044$. Cleavage flakes give very low first-order interference colors and, in convergent light, a negative biaxial interference figure with a small axial angle (2E = 5° to 20°).

Chemical Composition. Acid potassium magnesium aluminum orthosilicate, $H_2KMg_3Al(SiO_4)_3$. It also contains iron and fluorin.

Blowpipe Tests. Fusible (at 5) on thin edges and whitens. In the closed tube it gives a little water on intense ignition.

Easily decomposed by concentrated H_2SO_4.

Distinguishing Features. Phlogopite is darker than muscovite and lighter colored than biotite. Its occurrence in crystalline limestone is characteristic.

Uses. Phlogopite is used principally as an insulator in electrical apparatus. Canada is the only large producer of phlogopite.

Occurrence. 1. In crystalline limestones associated with spinel, graphite, chondrodite, etc.

2. In veins with apatite, calcite, and diopside.

CHLORITE,[1] $H_8(Mg,Fe)_5Al_2(SiO_6)_3$

Form. Chlorite crystals are monoclinic but pseudohexagonal in habit and resemble crystals of the micas. The mineral also occurs in disseminated flakes and in scaly masses.

[1] Chlorite is really the name of a group of minerals, but on account of the difficulty of distinguishing them they are all included under one heading.

Cleavage, perfect in one direction.

H. = 2 to 2½. **Sp. gr.** 2.8±.

Color, green of various tints and shades, varying from almost white to almost black.

Cleavage laminæ are flexible, but not elastic.

Optical Properties. $n_\gamma(1.596) - n_\alpha(1.585) = 0.011$. Fragments are irregular, green in color with faint pleochroism, and very low (often Berlin blue) first-order interference colors. Cleavage flakes in convergent light give an interference figure which is either uniaxial or biaxial with a small axial angle (2E = 0°–60°).

Chemical Composition. Acid magnesium and iron aluminum silicate. The composition varies for different chlorites; for one of them (clinochlore) the formula is $H_8(Mg,Fe)_5Al_2(SiO_6)_3$. In some varieties chromium and ferric iron partly replace the aluminum.

Blowpipe Tests. Fusible with difficulty (at 5½). In the closed tube gives about 12 per cent. of water at a high temperature.

Decomposed by H_2SO_4.

Distinguishing Features. Chlorite is characterized by its perfect cleavage, absence of elasticity in the cleavage flakes, and green color.

Occurrence. 1. A secondary mineral in igneous rocks, formed by the alteration of such silicates as biotite, hornblende, augite, etc.

2. In schists, often forming independent rock masses, the chlorite schists. These are formed from original basic igneous rocks.

ANTIGORITE, $H_4Mg_3Si_2O_9$

Form. Antigorite has never been found in crystals, though it often occurs pseudomorphous after other crystallized minerals. It is usually compact or granular massive, but also occurs in fibrous, columnar, and lamellar forms. It is the main constituent

of serpentine, which is properly considered a rock rather than a mineral.

H. = 3 to 4. **Sp. gr.** 2.5±.

Color, green of various tints and shades, from greenish-white to greenish-black. It is also often yellow, brown, or red, and the color is not apt to be uniform, but is often in spots and streaks.

Optical Properties. $n_\gamma(1.571) - n_\alpha(1.560) = 0.011$. Fragments are irregular, or prismatic with parallel extinction and positive elongation. The interference colors are low first-order. The irregular fragments show aggregate structure between crossed nicols.

Chemical Composition. Acid magnesium silicate, $H_4Mg_3Si_2O_9$; (H_2O = 12.9 per cent.). Part of the magnesium is usually replaced by ferrous iron. Some analyses show a little aluminum and some a little calcium. These constituents are largely due to residual pyroxenes.

Analyses of Antigorite

MgO	FeO	CaO	Al_2O_3	Fe_2O_3	SiO_2	H_2O	Misc.
42.6	0.1	0.1	...	0.3	42.0	14.7	
36.5	1.9	...	5.1	...	42.9	13.2	NiO = 0.6
41.2	2.4	...	...	...	41.3	14.5	
36.8	7.2	...	2.6	...	41.6	12.7	Cr_2O_3 = tr.

Blowpipe Tests. In the closed tube it gives water at a high temperature.

Decomposed by HCl with the separation of non-gelatinous silica.

Distinguishing Features. Antigorite is distinguished by its green color, moderate hardness (4), and its mottled, veined, or compact massive structure.

Uses. Serpentine is used as an ornamental stone.

Occurrence. 1. An alteration product of olivine and to a less

extent of bronzite, forming the metamorphic rock serpentine from original peridotite.

2. A secondary mineral in seams and veins and on the border of serpentine rocks.

3. An alteration product of diopside and forsterite in crystalline limestones; these form the rocks known as ophicalcites.

Chrysotile, $H_4Mg_3Si_2O_9$

Form. Chrysotile occurs in seams and always has a fibrous structure.

H. = $2\frac{1}{2}$. **Sp. gr.** 2.2±.

Color, green to golden yellow.

Optical Properties. $n_\gamma(1.55) - n_\alpha(1.54) = 0.01$. Fragments are needles with parallel extinction and positive elongation.

Chemical Composition. Chrysotile is dimorphous with antigorite and has the same chemical composition, $H_4Mg_3Si_2O_9$. (H_2O = 12.9 per cent.). Ferrous iron may replace part of the magnesium.

Blowpipe Tests. Fusible (at 6) in minute splinters.

Decomposed by HCl with the separation of fibers of silica.

Distinguishing Features. Chrysotile is distinguished from antigorite by its fibrous structure and by the difference in optical properties. From other fibrous minerals it is usually distinguished by its association in serpentine rocks. The parallel extinction and high water content distinguish it from tremolite asbestos.

Uses. Chrysotile is one of the minerals included under the term abstestos, which is so extensively used as a refractory.

Occurrence. 1. In seams and veins in serpentine rocks, associated with antigorite. Thetford, Ontario.

TALC, $H_2Mg_3(SiO_3)_4$

Form. Talc is found and in scales, in foliated, compact, or fibrous masses. Distinct crystals are exceedingly rare.

Cleavage, perfect in one direction.

H. = usually 1, but sometimes 4. **Sp. gr.** 2.7±.

Color, white, gray, or pale green. Luster, pearly.

Optical Properties. $n_\gamma(1.59) - n_\alpha(1.54) = 0.05$. Cleavage flakes give a negative biaxial interference figure with a small axial angle (2E = 10°–20°).

Chemical Composition. Acid magnesium metasilicate, $H_2Mg_3(SiO_3)_4$; (H_2O = 4.8 per cent.). It usually contains iron and aluminum in small quantities.

Blowpipe Tests. Fusible (at 5½) on thin edges. In the closed tube gives water on intense ignition. Heated intensely with cobalt nitrate solution, white varieties give a faint pink color.

Not decomposed by acids.

Distinguishing Features. Talc is characterized by its soapy feel. It can be distinguished from pyrophyllite by blowpipe or chemical tests.

Uses. Talc is used for soap, French chalk, talcum powder, and in the form of soapstone as a refractory material. A fibrous variety (agalite) is used in the manufacture of paper. The United States is the principal producer of talc and soapstone. In this country New York, Virginia, and Vermont lead.

Occurrence. 1. A secondary mineral occurring as an alteration product of various silicates such as antigorite, enstatite, and tremolite (including actinolite).

2. In schists often forming the rock masses known as talc schists and soapstones.

Pyrophyllite, $HAl(SiO_3)_2$

Form. In radiated forms and compact masses, but not in distinct crystals.

H. = 1½. **Sp. gr.** 2.8±.

Color, white, yellow, gray, brown. Luster, pearly.

Optical Properties. $n_\gamma(1.59) - n_\alpha(1.57) = 0.02$. Fragments

are prismatic with parallel extinction and positive elongation. The interference colors are low first-order.

Chemical Composition. Acid aluminum metasilicate, $HAl(SiO_3)_2$; (H_2O = 5.0 per cent.).

Blowpipe Tests. Infusible, often exfoliates. In the closed tube it gives water on intense ignition. Heated with cobalt nitrate solution it becomes deep blue.

Partially decomposed by H_2SO_4.

Distinguishing Features. Pyrophyllite is so much like talc in appearance that it is usually necessary to make the cobalt nitrate test for aluminum in order to prove its identity.

Occurrence. 1. In schistose metamorphic rocks.

2. In igneous rocks as a product of hydrothermal alteration.

Chondrodite, $Mg_5(F,OH)_2(SiO_4)_2$

Form. Chondrodite occurs in disseminated crystals and grains, but is also sometimes massive. Crystals are monoclinic, equidimensional, and rather complex. An interesting feature of the crystals is that the angle β (the angle between the a- and c-axes) is 90°.

H. = 6 to 6½. **Sp. gr.** 3.20±.

Color, red, orange, yellow, brown.

Optical Properties. $n_\gamma(1.639) - n_\alpha(1.607) = 0.032$. Fragments are irregular and colorless, or yellow with slight pleochroism. The interference colors are bright.

Chemical Composition. Basic magnesium orthosilicate, $Mg_5(F,OH)_2(SiO_4)_2$ or $Mg(F,OH)_2 \cdot 2Mg_2SiO_4$. Iron replaces part of the magnesium and hydroxyl part of the fluorin.

Blowpipe Tests. Infusible. In the closed tube it gives a little water (about 1.3 per cent.) at a high temperature. In the closed tube with $NaPO_3$ it etches the inside of the tube.

Gelatinizes with HCl.

Distinguishing Features. Chondrodite may often be recognized by its characteristic occurrence in crystalline limestones.

From garnet it may be distinguished by its low specific gravity and by optical tests.

Occurrence. 1. In crystalline limestones with phlogopite, spinel, etc. Tilly Foster mine, Brewster, N. Y.

Kaolinite, $H_4Al_2Si_2O_9$

Form. Kaolinite is sometimes found in minute pseudo-hexagonal (monoclinic) crystals of tabular habit. Figure 568 represents crystals found by the author at Argentine, Kansas, in a dolomitic limestone. The usual occurrence of kaolinite is in clay-like masses.

H. = 2 to 2½. **Sp. gr.** 2.6±.

Color, white, grayish, yellowish, etc. Luster, pearly to dull.

Optical Properties. $n_\gamma(1.567) - n_\alpha(1.561) = 0.006$. Fragments are irregular and show aggregate structure beween crossed nicols.

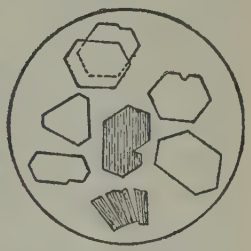


FIG. 568.—Kaolinite crystals (x 500).

Chemical Composition. Acid aluminum silicate, $H_4Al_2Si_2O_9$; ($H_2O = 14.0$ per cent.). Iron is often present in small amounts and thus it grades into nontronite ($H_4Fe_2Si_2O_9$).

Blowpipe Tests. Infusible if pure. Heated with cobalt nitrate solution it becomes deep blue. In the closed tube it gives water.

Insoluble in acids.

Distinguishing Features. Soft scaly masses of minute crystals with pearly luster are characteristic of kaolinite. It resembles halloysite, sericite, and alunite and as a rule can only be distinguished by optical tests.

Uses. Kaolin, a mixture of kaolinite and other aluminum silicates with more or less quartz, feldspar, etc., is used in the manufacture of porcelain, china, and pottery.

Occurrence. 1. A secondary mineral formed from the feldspars and other silicates, probably by the action of meteoric water.

Halloysite, $H_4AlSi_2O_9(H_2O)_x$

Form. Halloysite is the amorphous equivalent of kaolinite. It occurs in a massive form and occasionally shows colloform structure in cavities.

H. = 1 to 2. **Sp. gr.** 2.2±.

Color, white, gray, yellowish, reddish, etc.

Optical Properties. n = 1.55±. Fragments are irregular and dark between crossed nicols.

Chemical Composition. Acid aluminum silicate with a variable amount of adsorbed (or dissolved) water. $H_4Al_2Si_2O_9(H_2O)_x$. (Total water = 15.0 to 25.0 per cent.).

Blowpipe Tests. Infusible if pure. It turns blue when ignited with cobalt nitrate solution. Yields abundant water in the closed tube.

Decomposed by HCl.

Distinguishing Features. Halloysite is distinguished from kaolinite by optical tests and by its higher water content.

Uses. Halloysite is the principal constituent of some clays.

Occurrence. 1. In sedimentary beds. Lawrence county, Indiana.

2. In veins in decomposed igneous rocks. Stone Mountain, Georgia.

Garnierite, $H_2(Ni,Mg)SiO_4 \cdot H_2O$

Form. Garnierite occurs in earthy masses and has never been found in distinct crystals, though the polarizing microscope proves it to be crystalline.

H. = 2 to 3. **Sp. gr.** 2.5±.

Color, bright green to pale green.

Optical Properties. n about 1.59. Fragments are irregular, greenish in color, and show aggregate structure in polarized light.

Chemical Composition. A hydrous acid nickel and magnesium orthosilicate, $H_2(Ni,Mg)SiO_4 \cdot H_2O$. (Ni = 10 to 35 per cent.).

Blowpipe Tests. Infusible. Heated on charcoal it becomes magnetic. In the closed tube it blackens and yields water. The borax bead is violet when hot.

Partially decomposed by HCl.

Distinguishing Features. Garnierite is usually distinguished by its apple green color and earthy appearance.

Uses. Next to pentlandite, garnierite is the chief ore of nickel. The French colony of New Caledonia is the only important locality.

Occurrence. 1. A secondary mineral associated with serpentinized peridotites (it is probably an alteration product of nickel-bearing olivine). Riddles, Oregon.

CHRYSOCOLLA, $CuSiO_3 \cdot 2H_2O$

Form. Chrysocolla is a cryptocrystalline mineral occurring in seams and in incrustations which sometimes have a colloform surface. Its amorphous equivalent is a mineral called *cornuite.*

H. = 2 to 4. **Sp. gr.** 2.1±.

Color, bluish-green or greenish-blue.

Optical Properties. $n_\gamma(1.57) - n_\alpha(1.46) = 0.11$. Fragments are irregular, and usually show aggregate structure in polarized light.

Chemical Composition. Hydrous copper metasilicate, $CuSiO_3 \cdot 2H_2O$; Cu = 36.1 per cent., H_2O = 20.5 per cent.).

Blowpipe Tests. Infusible. Colors the flame green. In the closed tube it blackens and gives water.

Decomposed by HCl without gelatinization.

Distinguishing Features. Chrysocolla resembles turquois but is distinguished from it by its inferior hardness.

Uses. Chrysocolla is one of the so-called oxidized ores of copper.

Occurrence. 1. A secondary mineral often associated with malachite, azurite, and cuprite, and usually found in the upper workings of mines. Gila county, Arizona.

Glauconite, $KFe'''(SiO_3)_2 \cdot (H_2O)_x$

Form. Glauconite occurs in disseminated grains or in loosely cemented, sandy deposits called "greensand." The grains often have the form of foraminiferal shells.

H. = 2. **Sp. gr.** 2.3±.

Color, green to dark green.

Optical Properties. $n_\gamma(1.628) - n_\alpha(1.610) = 0.018$ Fragments are green with aggregate polarization.

Chemical Composition. Potassium ferric silicate with variable amounts of water; probable formula, $KFe'''(SiO_3)_2 \cdot (H_2O)_x$; ($K_2O$ = 5 to 8 per cent.). Aluminum replaces part of the iron. Sodium, ferrous iron, and magnesium are usually present, probably as a replacement of the potassium.

Blowpipe Tests. Easily fusible before the blowpipe to a black magnetic glass. In the closed tube yields water (6 to 10 per cent.). Practically insoluble in HCl.

Distinguishing Features. The little rounded green pellets are characteristic. It resembles some varieties of chlorite but has higher double refraction.

Uses. As a fertilizer. On account of the high potash content it may in the future be used for potassium salts.

Occurrence. 1. In sandstones, sands, clays, and limestones. It is marine in origin and is forming in the ocean at a depth of about 100 fathoms. Beds of "greensand" occur in the Cretaceons of New Jersey.

Apophyllite, $(H,K)_2Ca(SiO_3)_2 \cdot H_2O$

Form. Usually occurs in distinct crystals in cavities and along seams. Apophyllite crystallizes in tetragonal crystals of varying habit. Usual forms: $a\{100\}$, $y\{310\}$, $p\{111\}$, $c\{001\}$. Interfacial angles: $cp(001 : 111) = 60° 32'$; $ap(100 : 111) = 52° 0'$; $pp(111 : 1\bar{1}1) = 76° 0'$; $ay(100 : 310) = 18° 26'$. (Figs. 569—572).

Cleavage, perfect in one direction parallel to {001}.

H. = 4½ to 5. **Sp. gr.** 2.3±.

Color, colorless or white. Luster of (001) face, pearly; of other faces, vitreous.

Optical Properties. $n_\gamma(1.535) - n_\alpha(1.533) = 0.002$. Fragments are square or rectangular, and are either dark between crossed nicols or have low first-order interference colors. Cleavage flakes give a positive uniaxial interference figure in convergent light.

Chemical Composition. A hydrous acid calcium metasilicate, $(H,K)_2Ca(SiO_3)_2 \cdot H_2O$. A little potassium replaces part of the hydrogen and some analyses show a little fluorin.

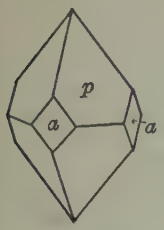


Fig. 569.

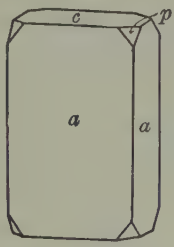


Fig. 570.

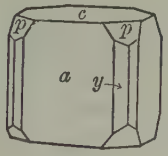


Fig. 571.

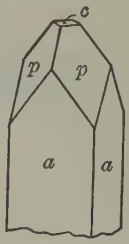


Fig. 572.

Figs. 569–572.—Apophyllite.

Blowpipe Tests. Easily fusible (at 2) with exfoliation to a white enamel. In the closed tube it yields water (about 16 per cent.).

Decomposed by HCl with the separation of non-gelatinous silica.

Distinguishing Features. The tetragonal crystals with perfect basal cleavage are highly characteristic of apophyllite.

Occurrence 1. In cavities of basic igneous rocks associated with zeolites. West Paterson, New Jersey.

ZEOLITE GROUP

Under the zeolites are included a number of well crystallized hydrous silicates of aluminum with calcium and the alkalies,

which are chemically similar to the feldspars except for the water of crystallization. They are characterized by low specific gravity (2 to 2.5) and moderate hardness (3 to 5½).

They are all decomposed by HCl with the separation of slimy or gelatinous silica and are easily fusible (at 2 to 3) with intumescence, hence the name *zeolite* from the Greek word meaning *to boil.*

The zeolites are usually found as secondary minerals in cavities of such basic igneous rocks as basalts and diabases. Table Mt. at Golden, Colorado, and Bergen Hill, New Jersey, are prominent localities for zeolites.

Heulandite, $H_4CaAl_2(SiO_3)_6 \cdot 3H_2O$

Form. Heulandite crystallizes in the monoclinic system. Usual forms: $b\{010\}$, $c\{001\}$, $t\{201\}$, $s\{\bar{2}01\}$, $m\{110\}$. Angles: $ct(001:201) = 63° 40'$; $cs(001:\bar{2}01) = 66° 0'$; $bm(010:110) = 68° 2'$. The habit is usually thick tabular parallel to {010}. The unsymmetrical outline of Fig. 573 is characteristic.

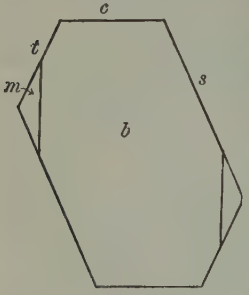


FIG. 573.—Heulandite.

Cleavage, perfect in one direction parallel to {010}.

H. = 3½ to 4. **Sp. gr.** 2.2±.

Color, colorless, white, pale brown, reddish. Luster pearly on the (010) face.

Optical Properties. $n_\gamma(1.505) - n_\alpha(1.498) = 0.007$. Fragments are plates with low first-order interference colors. Cleavage flakes give a positive biaxial interference figure in convergent light.

Chemical Composition. Hydrous acid calcium metasilicate, $H_4CaAl_2(SiO_3)_6 \cdot 3H_2O$; ($H_2O$ = 14.8 per cent.). The calcium is usually partly replaced by small amounts of sodium, potassium, and strontium. Brewsterite is a similar isomorphous mineral with the calcium largely replaced by strontium and barium.

Blowpipe Tests. Easily fusible (at 3) with exfoliation to a white enamel. In the closed tube it gives water.

Decomposed by HCl with the separation of non-gelatinous silica.

Distinguishing Features. The monoclinic crystals with pearly luster and unsymmetrical outlines are characteristic.

Occurrence. 1. A secondary mineral in cavities of basic igneous rocks, associated with other zeolites.

Stilbite, $H_4(Ca,Na_2)Al_2(SiO_3)_6 \cdot 4H_2O$

Form. Stilbite usually occurs in indistinct crystals or in sheaf-like aggregates. Crystals are monoclinic but are pseudo-orthorhombic by twinning. The symmetrical outline of Fig. 574 is typical of stilbite.

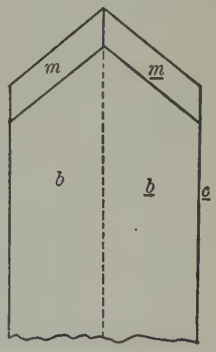


Fig. 574.—Stilbite.

Cleavage, in one direction fairly good.

H. = 3½ to 4. **Sp. gr.** 2.1±.

Color, white, yellow, brown.

Optical Properties. $n_\gamma(1.500) - n_\alpha(1.494) = 0.006$. Fragments are prismatic with parallel extinction and negative elongation. The interference colors are upper first-order.

Chemical Composition. Hydrous acid calcium and sodium aluminum metasilicate, $H_4(Ca,Na_2)Al_2(SiO_3)_6 \cdot 4H_2O$; ($H_2O$ = 17.2 per cent. if Ca:Na = 6:1).

Blowpipe Tests. Easily fusible (at 3) with exfoliation to a white enamel. In the closed tube it yields water.

Decomposed by HCl with the separation of non-gelatinous silica.

Distinguishing Features. The symmetrical outline and sheaf-like grouping of the crystals is characteristic. The cleavage is not as perfect as that of heulandite.

Occurrence. 1. A secondary mineral in cavities and seams of igneous rocks, especially basalts and diabases.

2. In miarolitic cavities of granites and pegmatites as the last mineral to be formed.

Chabazite, $(Ca,Na_2)Al_2(SiO_3)_6 \cdot 6H_2O$

Form. Chabazite practically always occurs in distinct cube-like rhombohedral crystals ($10\bar{1}1 : \bar{1}101 = 85° 14'$ (Fig. 575). Penetration twins with $\dot{c}$ as the twin-axis are common.

H. = 4½. **Sp. gr.** 2.1±.

Color, white, colorless, pink, red.

Optical Properties. $n_\gamma(1.488) - n_\alpha(1.485) = 0.003$. Fragments are nearly square rhombs or are irregular. The interference colors are low first-order.

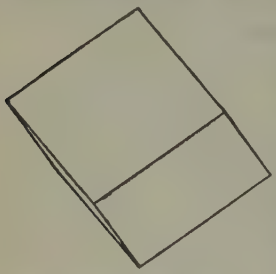


Fig. 575.—Chabazite.

Chemical Composition. Hydrous calcium-sodium aluminum metasilicate, $(Ca,Na_2)Al_2(SiO_3)_4 \cdot 6H_2O$. A little potassium is usually present.

Blowpipe Tests. Fuses (at 3) with intumescence to a white glass. In the closed tube it yields water (about 21 per cent.). Decomposed by HCl with the separation of non-gelatinous silica.

Distinguishing Features. The cube-like rhombohedral crystals are characteristic. It is distinguished from calcite by the absence of perfect cleavage as well as by optical tests.

Occurrence. 1. A secondary mineral in cavities and seams of igneous rocks associated with the other zeolites.

Analcite, $NaAl(SiO_3)_2 \cdot H_2O$

Form. Analcite occurs in attached crystals or in druses lining cavities and seams. It is isometric in crystallization; the only common form is the trapezohedron, {211}, the same form that is common on garnet (Fig. 576).

H. = 5 to 5½. **Sp. gr.** 2.25 ±.

Color, colorless or white.

Optical Properties. $n = 1.487$. Isotropic. Fragments are irregular and dark between crossed nicols.

Chemical Composition. Hydrous sodium aluminum metasilicate, $NaAl(SiO)_3)_2 \cdot H_2O$; ($H_2O$ = 8.2 per cent.).

Blowpipe Tests. Fusible at 3½ to a colorless glass. In the closed tube it yields water.

Decomposed by HCl with the separation of gelatinous silica.

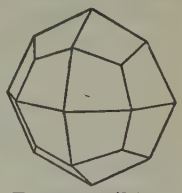


FIG. 576.—Analcite.

Distinguishing Features. Analcite is similar in form to leucite and garnet; from these it is distinguished by its mode of occurrence.

Occurrence. 1. As secondary mineral in seams and cavities of basic igneous rocks.

2. As late magmatic mineral in certain diabases and basalts.

Natrolite, $Na_2Al_2Si_3O_{10} \cdot 2H_2O$

Form. This mineral occurs in divergent crystal groups or in fibrous masses. Crystals are orthorhombic but apparently tetragonal (110 : $1\bar{1}0$ = 88° 45′). The habit is long prismatic or acicular, terminated by the low bipyramid {111}. Figure 577 represents a typical natrolite crystal. The presence of the side pinacoid *b* proves it to be orthorhombic.

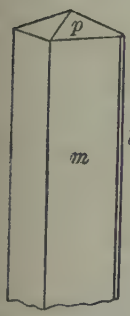


FIG. 577.—Natrolite.

H. = 5. **Sp. gr.** 2.25±.

Color, colorless or white.

Optical Properties. $n_\gamma(1.488) - n_\alpha(1.475) = 0.013$. Fragments are prismatic or acicular with parallel extinction, positive elongation, and bright interference colors.

Chemical Composition. Hydrous sodium aluminum silicate, $Na_2Al_2Si_3O_{10} \cdot 2H_2O$; ($H_2O$ = 9.5 per cent.).

Blowpipe Tests. Easily fusible (at 2½) to a colorless glass giving a yellow flame. In the closed tube it yields water.

Decomposed by HCl and on evaporation the solution gelatinizes.

Distinguishing Features. Natrolite is distinguished from the other zeolites and from aragonite by the square cross-section of the crystals.

Occurrence. 1. A secondary mineral occurring in cavities of basalts and diabases.

Titanite, $CaTiSiO_5$

Form. Titanite or sphene occurs in attached crystals, and in disseminated crystals and grains. Crystals are monoclinic of varied habit, and are usually acute rhombic in cross-section. The envelope-shaped form of Fig. 578 is typical. Usual forms: $c\{001\}$, $m\{110\}$, $n\{111\}$. Interfacial angles: mm $(110 : \bar{1}10) = 66° 29'$; nn $(111 : 1\bar{1}1) = 43° 49'$; cm $(001 : 110) = 65° 30'$; cn $(001 : 111) = 38° 16'$.

FIG. 578.—Titanite.

Cleavage. There is sometimes prominent parting in two directions at angles of 54°.

H. = 5 to 5½. **Sp. gr.** 3.45±.

Color, varying tints and shades of yellow and brown. Luster, adamantine or subadamantine.

Optical Properties. $n_\gamma(2.00) - n_\alpha(1.88) = 0.12$. Fragments are irregular and slightly pleochroic with very high-order interference colors.

Chemical Composition. Calcium titano-silicate, $CaTiSiO_5$, a salt of $H_2Si_2O_5$ in which one atom of silicon is replaced by one of titanium. Iron is usually present in small amounts.

Blowpipe Tests. Fusible (at 4) to a colored glass. It gives a violet $NaPO_3$ bead in R.F.

Partially soluble in HCl.

Distinguishing Features. Titanite is often distinguished by the acute-angled crystals which are envelope-shaped.

Occurrence. 1. A common and widely distributed accessory constituent of plutonic igneous rocks (granites, granodiorites, diorites, syenites).

2. In clefts and seams or disseminated through metamorphic rocks, probably often formed from titaniferous pyroxenes.

MINERALOIDS

A mineral may be defined as a naturally occurring, homogeneous, inorganic substance of definite or fairly definite chemical composition. Now there are some homogeneous substances found in the earth's outer shell which do not fulfill the conditions of the above definition, yet they deserve the attention of the student of mineralogy. Among these substances are the glasses and the hydrocarbons. The glasses are inorganic but are too indefinite in chemical composition to be considered minerals, while the hydrocarbons, though occasionally of definite composition, are organic. These two classes of substances may be treated in an appendix under the term **mineraloid.**

Glass

Form. Amorphous, usually massive and structureless, but sometimes vesicular, spheroidal (perlitic), or banded.

H. = 5 to 7. **Sp. gr.** = 2.2 to 2.7.

Color, colorless, gray, black; sometimes green, brown, or red. Translucent to transparent on thin edges.

Luster. Vitreous to resinous, dull if devitrified.

Optical Properties. $n = 1.48$ to 1.67 (increases in general with decrease of SiO_2). Usually isotropic but may be doubly refracting due to strain, especially the perlitic varieties.

Chemical Composition. Variable, contains SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, and K_2O in amounts comparable to

Table of Analyses of Natural Glass

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	Misc.
Rhyolitic obsidian	75.8	12.4	0.2	1.3	0.3	0.8	4.0	4.6	0.4	
Rhyolitic pitchstone	71.6	13.1	0.7	0.3	0.1	0.7	3.8	4.1	5.5	
Andesitic perlite	65.1	15.7	2.2	1.9	1.4	3.6	2.9	4.0	2.4	
Trachytic obsidian	61.2	18.0	1.3	4.5	0.4	1.9	6.5	5.9	0.5	MnO = 0.4
Basaltic obsidian	53.8	13.5	3.0	7.4	6.5	10.3	3.2	0.6	0.6	TiO = 0.2
Basaltic obsidan	50.7	12.0	3.4	8.1	7.3	12.4	2.7	0.2	0.5	TiO_2 = 1.7

those found in various types of igneous rocks ranging from the high silica content of rhyolite to the relatively low silica content of basalt. Water is low in obsidian, but comparatively high in pitchstone.

Blowpipe Tests. The fusibility of volcanic glass is characteristic. It is fusible to a vesicular enamel, but this enamel on further heating is infusible, which is due to the fact that the water is driven off. In the closed tube it gives more or less water (0.5 to 5 per cent.).

Insoluble in acids. Tests for silica and the metals can be obtained by making a sodium carbonate fusion (see p. 49). The alkalies must be determined in a separate sample by fusion with NH_4Cl and $CaCO_3$.

Distinguishing Features. Opal is about the only mineral ordinarily confused with volcanic glass. These two can easily be distinguished by their fusibility. (Opal is infusible.) The index of refraction of glass, though variable, is always higher than that of opal.

Occurrence. 1. Volcanic glass is an igneous rock occurring in surface flows or as selvage on lavas and occasionally in dikes (pitchstones). It has been formed by the rapid cooling of the molten magma, and as a consequence some of the water of the original magma is usually retained.

Hydrocarbons

The naturally occurring hydrocarbons vary from **natural gas** [largely methane (CH_4) with variable amounts of ethane, (C_2H_6), carbon dioxid, nitrogen, argon, neon, and helium] through liquid **petroleum** (largely hydrocarbons of the methane or paraffin series with the general formula C_nH_{2n+2}) and viscous **maltha** to solid hydrocarbons which may be divided into four fairly well-defined groups, *viz.*, resins, waxes, asphaltum, and coal.

Resins. The resins are oxygenated hydrocarbons. They are amorphous and have a resinous luster. The specific gravity

is slightly above unity (1.00 to 1.25). They burn or melt easily and are more or less easily soluble in alcohol, ether, and turpentine.

Of the various fossil resins **amber** is the best known on account of its well-known uses. It varies from a pale yellow to deep brown and has a specific gravity of about 1.05. The best amber is found along the Baltic coast of Prussia. It has been formed by an extinct species of pine.

Other fossil resins include **gum copal** from Africa and **kauri gum** from New Zealand used in varnishes. There are also many local names used for various resins.

Mineral waxes. Ozocerite or ozokerite is the best known representative of this group of hydrocarbons which are natural paraffins with impurities. Ozocerite is the name applied to a soft brown mineral wax from Galicia, also found in southern Utah. It is soluble in ether and has a specific gravity of 0.85 to 0.95. Refined ozocerite is used in the manufacture of candles, ointments, and as an insulator for electrical apparatus.

Asphaltum or asphalt is a general name for a great variety of black, solid, more or less oxygenated hydrocarbons. They include besides the well-known Trinidad Lake asphalt, other varieties which have received special names such as albertite, gilsonite, grahamite, manjak, wurtzilite, and many others of local importance. Each of these has special characters of its own, but they are all similar with a hardness of 1 to 2½, specific gravity of 1.0 to 1.8. They melt easily and burn with a disagreeable odor. They are more or less soluble in alcohol, ether, turpentine, carbon bisulfid, and chloroform. The relative solubility in these various solvents is the best method of distinguishing the various kinds of asphaltums.

Asphaltum occurs in veins usually and rarely in lake deposits as on Trinidad Island. Asphaltum and semi-solid hydrocarbons also occur as impregnation of sandstones or limestones. These bituminous sandstones and limestones have been used for paving in some parts of the United States.

The oil shales found so abundantly in western Colorado should also be mentioned here. On distillation they yield gas, crude oil, and ammonia. The crude oil on refining furnishes gasoline, burning oils, and paraffin wax.

Coal. Finally we have the coals which vary from lignite through subbituminous, bituminous, and semianthracite to anthracite. The chemical compounds in coal are for the most part unknown. Coal consists largely of carbon, hydrogen, and oxygen, with small amounts of nitrogen and sulfur. Analyses are usually given in a proximate form: moisture, volatile matter, fixed carbon, and ash.

The specific gravity of coal varies from about 1.2 to 1.7. The hardness reaches 2 to 2½ in anthracite.

Coal is distinguished from other hydrocarbons by the fact that it is practically insoluble in the organic solvents (ether, alcohol, etc.).

Coal occurs in beds and so must be ranked as a rock as well as a mineraloid. Anthracite may be said to constitute a kind of metamorphic coal.

Coal is known to be of vegetable origin. All gradations have been traced from peat through lignite into various members of the coal series. There is, however, disagreement as to the details of the formation of coal.

Salts of Organic Acids. The discussion of mineraloids would be incomplete without a brief reference to the salts of certain organic acids. One of these, calcium oxalate, occurs in plant tissues and is also found in coal beds in monoclinic crystals which have received the name **whewellite.** They have the composition $CaC_2O_4 \cdot H_2O$.

PART III

THE OCCURRENCE, ASSOCIATION, AND ORIGIN OF MINERALS

A. GENERAL PRINCIPLES

The determination of the properties of a mineral does not end its investigation. There still remains to be determined the problem of its rôle in nature. What is its relation to associated minerals and how has it been formed? This is to some extent an independent subject, for with the possible exception of amorphous minerals of colloidal origin, the essential properties of a mineral are not dependent on its previous source or history. The facts of occurrence and association are important from the scientific standpoint and also from the economic standpoint in case the mineral or one of its associates is of commercial value.

A great many of the subjects considered in the following pages are treated under the head **petrography,** the science that deals with rocks especially from the descriptive side. A broader treatment of the whole subject of mineral occurrences, including mineral deposits as well as rocks is attempted.

1. ASSOCIATION OF MINERALS

The minerals of rocks and other mineral deposits occur together in more or less definite association one with another. Many of the associations are so characteristic that the experienced mineralogist makes use of the facts in determining minerals. Franklinite, for example, is practically always associated with willemite and zincite (ZnO). Lepidolite, tourmaline, microcline, albite, spodumene, and beryl are characteristic of granite pegmatites. Nepheline occurs with the feldspars in igneous rocks and is never found with quartz. The zeolites

occur largely with datolite, apophyllite, prehnite, calcite, chalcedony, and quartz as secondary minerals in basalts and related rocks. Chondrodite is almost invariably found with phlogopite and spinel in metamorphic limestones.

The term **paragenesis** is used as a general term for the association of minerals with special reference to their occurrence and origin.

2. ORDER OF SUCCESSION

Not only the association but also the order of succession of minerals is often characteristic. In many copper ore deposits, for example, the order in which the minerals have been formed is as follows: (1) pyrite, (2) chalcopyrite, (3) bornite, (4) chalcocite. In most ore deposits the ore-minerals have been formed after quartz and the silicates, although some of the silicates, among them sericite, chlorite, tremolite, and antigorite, are apparently formed after the ore-minerals.

The order of succession of the minerals of a deposit combined with the geology gives valuable clues to the history of the deposit.

3. PROCESSES OF MINERAL FORMATION

Minerals may be formed in various ways. Some have been formed from water solution (veins, spring deposits, secondary minerals in cavities) either by concentration of solutions or by chemical reactions. Some have been formed by separation from a molten magma (minerals of the igneous rocks). The magma is to be looked upon as a solution of certain compounds in others, for the minerals separate out in the order of solubility rather than of fusibility. Others have been formed by organisms. Still others have been formed by the chemical readjustment incident to metamorphism. A few minerals are the result of exhalations of gases in volcanic regions.

4. SYNTHESIS OF MINERALS

Besides filling up gaps in isomorphous groups and furnishing better material for study, the synthesis of a mineral often gives a

clue to its origin in nature. Most minerals have been produced artificially, but a few, such as tourmaline, have never been produced except in Nature's laboratory itself.

The methods of mineral synthesis differ greatly; the apparatus varies from a test-tube to the electric furnace. A general method is that of the sealed tube. A hard glass tube containing the proper substances is sealed up and heated in a bomb-furnace for several hours or days, or even weeks if necessary. Water vapor under pressure plays an important part in reaction, as it often seems to in nature. An example of this method is the production of artificial covellite (CuS) by heating powdered sphalerite (ZnS) in a water solution of copper sulfate. An atmosphere of CO_2 is used to prevent oxidation. After a few hours a blue-black powder (CuS) appears. The reaction is $ZnS + CuSO_4 = CuS + ZnSO_4$. This experiment was performed by the author in an attempt to explain covellite pseudomorphs after sphalerite found by him in the Joplin district. In such experiments geologic time is compensated for by increased temperature and pressure.

Some of the "basic" igneous rocks are easily reproduced, and such minerals as olivine, pyroxene, leucite, and plagioclase crystallize out from a molten mass of the proper constituents. Attempts to reproduce the "acid" igneous rocks on the other hand are not successful, for the magma solidifies as a glass. The lack of gases which were present in the natural magma accounts for the failure.

French mineralogists and chemists have been especially active in mineral synthesis. Moissan produced diamond by dissolving carbon in molten iron and the plunging the mass into water. Artificial rubies, sapphires, and other colored varieties of corundum are now made in Paris on a commercial scale. These were first successfully produced by Verneuil in 1904. Except for very minute bubbles they have exactly the same physical properties as the natural gems and are distinguished from them with great difficulty. Artificial stones resembling the emerald are easy to produce but they are really glass and not true artificial beryl.

Intermediate between the naturally occurring minerals and the so-called artificial minerals are the mineral substances formed on mine-tools, prehistoric implements, old coins, etc. Man has unintentionally furnished part of the material, but has not directed the conditions of the experiments, hence the term **accidental synthesis.** The author has identified cuprite, copper, malachite, azurite, and cerussite on buried Chinese coins of the seventh century found at Kiukiang, China. In the old Roman baths at the hot springs of Bourbonne-les-Bains, France, bronze coins thrown in the spring as votive offerings were found by Daubrée to be incrusted with such minerals as chalcocite, chalcopyrite, bornite, and tetrahedrite, and the conduits leading to the baths were lined with zeolites.

5. ALTERATION AND REPLACEMENT OF MINERALS

A mineral formed under one set of conditions may be unstable under another set of conditions. This accounts for the observed replacement of one mineral by another. Pyrite, for example, is unstable under oxidizing conditions and so in the oxidized zone we usually find it more or less altered to limonite, turyite, or sometimes to iron sulfates. If copper solutions are present it may be altered to chalcocite. Replacements in which there is a chemical relation between the original mineral and the replacing mineral are called **alterations.** The more common chemical changes involved in alteration are oxidation (sulfids to sulfates, sulfids to oxids, arsenids to arsenates, etc.), reduction (sulfates to sulfids, sulfids to metals, oxids to metals), carbonation (sulfids to carbonates), and hydration (anhydrous salts to hydrous salts). There are also more complex changes, some of which have received special names. The following may be mentioned as prominent examples of alterations: pyrite to limonite; galena to cerussite, usually through the intermediate stage of anglesite; sphalerite to smithsonite; bornite to chalcocite; copper to cuprite; calcite to smithsonite; olivine to antigorite (serpentinization); pyroxene to actinolite (uralitization); and feldspars to sericite (sericitization).

One of the best evidences of alteration and replacement is the occurrence of pseudomorphs. A **pseudomorph** is one mineral with the form of another, a false form as the name indicates. Thus limonite, an amorphous mineral, is often found in cubes. The explanation is that the cubes were originally pyrite and were altered to limonite by oxidation and hydration. Such a specimen is said to be a limonite pseudomorph after pyrite. Four general classes of pseudomorphs are recognized:

1. *Alteration pseudomorphs* with either a loss, gain, or interchange of some constituent. Examples of the three cases respectively: copper after azurite; malachite after cuprite; cerussite after galena.

2. *Paramorphic pseudomorphs* or *paramorphs.* A pseudomorph of one polymorphous mineral after another is called a paramorph. Example: calcite after aragonite.

3. *Substitution pseudomorphs.* An interchange of substance not involving alteration. Example: chalcedony after calcite.

4. *Incrustation pseudomorphs.* If one mineral incrusts another and then the original mineral is dissolved there remains a cavity which may afterward be filled by still another mineral. Example: quartz after fluorite.

The replacement of a fossil by a mineral is called a **petrifaction.** The more common minerals occurring as petrifactions are calcite, chalcedony, opal, quartz, limonite, pyrite, and collophane, and rarely such minerals as barite and sphalerite.

Fossil wood is usually preserved as opal and chalcedony, occasionally as quartz and rarely as calcite or dolomite. In New Mexico cuprified wood now made up of hematite, pyrite, bornite, chalcocite, and melaconite (amorphous CuO) is common in certain regions. The cell-structure of the wood is often preserved and sometimes the wood may be identified.

Fossil bone, as the author has recently discovered, is made up almost entirely of the mineral collophane. The structure of the bone is usually perfectly preserved. The original bone consists of calcium carbonophosphate and an organic substance called

ossein, one of the proteins. The fossilization of the bone consists of the elimination of the organic substance (some of it usually remains behind as a pigment) and an enrichment of the inorganic portion.

Replacement may take place on an extensive scale and in this way some of our prominent types of ore-deposits have been formed. Whole rock formations may be replaced by solutions. Many phosphorites, for example, have been formed by the action of phosphatic solutions upon limestones. Limestones may also be replaced by silica, usually in the form of chalcedony.

B. MINERAL OCCURRENCES INCLUDING ROCKS

No satisfactory classification of the various mineral occurrences can be made on account of the multiplicity of factors to be taken into account. For convenience, rocks and mineral deposits are treated under the following heads.

1. IGNEOUS ROCKS

General Discussion

The igneous rocks include all rocks that are the result of solidification of molten material on or in the earth's crust or outer shell. They are of especial importance because of the fact that they are the original source of the other two great groups of rocks, the sedimentary and the metamorphic. Igneous rocks are characterized by the presence of certain minerals which are practically absent from other rocks, by the massive appearance or absence of stratification and foliation, and also by the absence of fossils.

The prominent features of igneous rocks may be discussed under the following heads: (1) chemical composition, (2) mineral composition, (3) texture, (4) structure, and (5) mode of occurrence. These are the factors used in the description and classification of igneous rocks.

Chemical Composition.

Chemical analyses of igneous rocks are always recorded in the form of oxids. The nine principal oxids are: silica (SiO_2), alumina (Al_2O_3), ferric oxid (Fe_2O_3), ferrous oxid (FeO), magnesia (MgO), lime (CaO), soda (Na_2O), potassa (K_2O), and water (H_2O). Practically all igneous rocks also contain small amounts of titania (TiO_2), carbon dioxid (CO_2), baryta (BaO), manganous oxid (MnO), and phosphoric anhydrid (P_2O_5). The oxids are in chemical combination and do not exist free except in a few cases, the most prominent of which is free silica in the form of quartz. Among the various constituents silica predominates. It varies from a maximum of about 75 per cent. in granites and rhyolites to a minimum of about 40 per cent. in peridotites. Igneous rocks high in silica are **persilicic** (the so-called acid rocks), those low in silica, **subsilicic** (the so-called basic rocks), and those of intermediate silica content, **mediosilicic.** Granites and rhyolites, for example, are persilicic rocks, basalts, olivine gabbros, and peridotites, subsilicic rocks. Alumina in general is fairly constant, but is very low in peridotites and high in syenites. The iron oxids, magnesia, and lime are low in persilicic rocks and high in the subsilicic rocks. The alkalies (soda and potassa), on the other hand, are relatively high in persilicic rocks and almost lacking in the peridotites.

The following list of analyses will serve to show the range in chemical composition of the more common types of igneous rocks.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	Misc.
Granite (Pike's Peak)	73.9	13.6	0.3	0.4	0.1	0.2	2.5	8.0	0.5	0.1
Granodiorite (Mariposa Co., Cal.)	66.3	16.0	1.8	1.9	1.1	3.7	4.1	3.5	0.5	0.9
Syenite (Plauen, Saxony)	62.5	16.5	2.4	2.0	1.9	4.2	4.4	4.6	0.6	1.3
Diorite (Electric Peak)	58.1	18.0	2.5	4.6	3.5	6.2	3.6	2.2	0.9	1.2
Gabbro (Island of Skye)	52.8	17.8	1.2	4.8	4.8	12.9	3.0	0.5	1.2	0.5
Olivine gabbro (Birch)	45.7	16.4	0.7	13.9	11.6	7.3	2.1	0.4	0.9	1.1
Peridotite (Devonshire)	40.1	7.8	7.3	8.6	23.7	6.5	1.2	0.5	4.0	0 6

Igneous rocks are the result of the cooling and consequent

solidification of molten material called a **magma.** The original magma may be observed in active volcanoes. If the magma is cooled rapidly a glass is the result, but if the cooling is slow then crystallization takes place and crystals of various minerals are produced.

During the act of crystallization, which may be either very slow or relatively rapid, certain oxids combine to form silicates. The alkalies and lime combine with silica and alumina to form the feldspars; lime, magnesia, and the iron oxids combine with silica and alumina to form the ferromagnesian minerals, a collective term for pyroxene, hornblende, biotite, and olivine. Some of the ferric oxid combines with ferrous oxid to form magnetite. Silica remaining after these combinations have taken place crystallizes out in the form of quartz. In rare cases there is too much alumina to combine with silica and the alkalies and the other constituents and so corundum is formed. It must be admitted that this process is very complicated, especially when gases are present, for it is not always possible to predict the mineral composition from a chemical analysis.

Mineral Composition. Comparatively few minerals constitute the bulk of igneous rocks. Only a dozen or two minerals are found in quantity in the various igneous rocks even if we include the less common and unusual rock types.

The more important minerals of igneous rocks are:

1. *Essential Minerals.* Feldspars (orthoclase and plagioclase), pyroxene (augite, diopside, and hypersthene), hornblende, biotite, olivine, quartz, nepheline (rare), and leucite (rare).

2. *Accessory Minerals.* Magnetite, apatite, titanite, ilmenite, and zircon.

3. *Secondary Minerals.* Quartz, chalcedony, opal, calcite, zeolites, chlorite, sericite, antigorite, and kaolinite.

Texture. In addition to the chemical and mineralogical composition, the size, shape, and arrangement of the constituent minerals must be taken into account in the study of rocks. These features of a rock are collectively known as the **texture.** The

texture is important because it gives some indication of the physical conditions obtaining during the formation of the rock. A magma with a given chemical composition may form several distinct rock types depending upon the temperature, hydrostatic pressure, rate of cooling, presence of gases, etc.

Three main factors are involved in texture. In the first place there is the **degree of crystallization.** The rock may be made up entirely of glass, entirely of crystals, or any given proportion of the two. A second factor is the **magnitude of the crystals.** The crystals present may be very minute, small, or large, thus furnishing fine-grained rocks (less than 1 mm. in size), medium-grained rocks (between 1 mm. and 5 mm. in size), and coarse-grained rocks (greater than 5 mm. in size). The third factor is **fabric,** a term which denotes the relative size of the crystals and their shape and arrangement. If the crystals are of the same order of magnitude the rock is said to be **even-grained.** If the crystals are of different order of magnitude the fabric is said to be **porphyritic.** In this case the larger crystals are called **phenocrysts** and their matrix, which may contain more or less glass, is called the **groundmass.** The crystals themselves may be euhedral, subhedral, or anhedral, and if euhedral may be tabular, prismatic, or equant (equidimensional) in habit. The crystals may have a more or less parallel arrangement or may interpenetrate each other and thus form the **graphic texture.** In the volcanic glasses **spherulitic** aggregates of the feldspars are often present.

Structure. The larger features of igneous rocks are included under the term **structure.** It is obvious that no clear distinction can be made between the terms texture and structure. Most of the igneous rocks have a massive structure but in some of them banded, columnar, or spheroidal structures are present. These result largely from contraction on cooling. Many of the volcanic rocks, especially basalts, have a **vesicular** structure. The rock is filled with rounded cavities which are due to the escape of steam and other gases from the rock during its consolidation. If these

cavities at a later time are filled with minerals such as the zeolites, calcite, chalcedony, quartz, etc., the structure is said to be **amygdaloidal** (from the Greek word for almond).

Mode of Occurrence. According to the geological mode of occurrence igneous rock masses may be divided into three large groups; (1) extrusive, (2) injected, and (3) subjacent.

Extrusive rocks are igneous rocks that have been formed by the cooling of magmas on or very near the earth's surface. They are the well-known lavas found around recent volcanoes. The terms lava and **volcanic rock** should be restricted to extrusive rocks and should not be used as a synonym of igneous rock in general. The extrusive rocks comprise two general classes, fissure eruptions and central eruptions. The great basaltic lava fields of eastern Oregon and Idaho, northwestern India, and Iceland are fissure eruptions. The lavas have issued quietly through narrow fissures and probably were very fluid at the time of extrusion. Under central eruptions are included rock bodies formed by extrusion from a single vent. They comprise **volcanic cones, plugs,** and **surface flows.** The lavas formed during quiescent periods often alternate with beds of fragmental material, **volcanic ash,** which are due to explosive action. When consolidated the beds of volcanic ash become **tuffs.** The **volcanic neck** feeding the vent may be exposed by erosion.

The **injected rocks** form the smaller intrusions such as dikes, sills, and laccoliths. A dike is formed by the injection of a magma into a relatively narrow fissure not parallel to the bedding plane of a sedimentary rock. If the fissure is parallel to the bedding plane a **sill** is produced. The term **laccolith** is used for a dome-shaped intrusion which has bowed up the overlying strata.

The **subjacent** rock bodies comprise batholiths and stocks. A **batholith** is a large rock mass of indeterminate shape and size exposed by erosion in mountainous regions. Similar, but smaller masses are called **stocks.** They probably represent protruding portions of irregular batholiths. The formation of batholiths is a disputed question in geology. They may be injected but it

is better to use the term subjacent, proposed by Daly, which is non-committal as to origin.

The Classification of Igneous Rocks

A good many different classifications of igneous rocks have been proposed, but none can be considered satisfactory. There is much difference as to the relative value of the criteria used in the classification. Some emphasize texture while others almost disregard it, and in one widely used classification the geological mode of occurrence is the prominent feature. The principal difficulty in the classification of igneous rocks is the fact that they intergrade in all directions. They are aggregates of minerals in all proportions so that division lines between groups are necessarily arbitrary. It is necessary to establish certain arbitrary rock types and classify these in the most convenient way.

For megascopic and microscopic work in the absence of chemical analyses, mineral composition and texture are the two principal criteria used in the classification. The following diagram gives a convenient simple classification of the more common igneous rock types. Two main textures are recognized. In the **grained** rocks practically all the constituent minerals are large enough to be seen with the unaided eye, while in the **dense** rocks at least some of the constituents are too small to be seen without the microscope (more or less glass may be present). Porphyritic and non-porphyritic varieties of each class are given so that four kinds of texture are recognized. These extend in a horizontal direction.

The dense rocks (trachyte, rhyolite, andesite, auganite, and basalt) generally occur in surface flows, volcanic necks, etc. The grained rocks (syenite, granite, diorite, etc.) generally occur in stocks and batholiths and in the centers of large dikes and laccoliths. The intermediate porphyries occur in the smaller intrusions and in the interior of thick surface flows. Thus there is a general correlation between the texture and mode of occurrence but too much stress should not be laid upon it, for the correlation

Tabular classification of the more common igneous rock types

is only a general one. The classification of the rock should be based upon its intrinsic characters, that is upon characters that can be determined from the specimen itself. The geological mode of occurrence is a question of field geology. These two sets of equally important facts should be determined independently. If this is not done, incorrect conclusions may be drawn.

The vertical columns, on the other hand, contain all the rocks with a given mineral composition and generally speaking those with about the same chemical composition.

A Granite-Rhyolite Series.

This series includes all igneous rocks composed essentially of quartz and orthoclase with minor amounts of ferromagnesian minerals, and the corresponding glassy equivalents.

Granite is perhaps the most familiar of all igneous rocks because of its wide use as a building and ornamental stone. The two essential minerals of granite are quartz and orthoclase feldspar. Mica may or may not be present. Plagioclase is often present in addition to orthoclase and is distinguished from orthoclase by twinning striations and often by a color difference. The feldspars are white, gray, pink, or red, and largely determine the color of the rock, for the quartz is usually transparent. The ferromagnesian minerals commonly present are hornblende and biotite. Muscovite also is sometimes present. Rarer constituents include epidote and tourmaline. The minor accessories are apatite, zircon, titanite, and magnetite.

The chemical composition of an average granite is shown in the tabulation on page 423. Compared with other igneous rocks it is high in silica and alkalies.

The characteristic occurrence of granite is in batholiths and stocks.

With decrease in the amount of ferromagnesian minerals normal granite grades into a variety called **alaskite.** With increase in the amount of ferromagnesian minerals and consequent decrease in the quartz and orthoclase it passes into granodiorite.

With decrease in the amount of quartz and increase in orthoclas it passes through quartz syenite into syenite.

With decrease in the size of the mineral grains and the appear ance of one or more of the minerals in crystals of two generation the granites grade imperceptibly through granite porphyrie and rhyolite porphyries into rhyolites.

Rhyolite. The rhyolites are the dense or fine-grained equiva lents of granites. The texture varies from porphyritic throug felsitic into glassy. Flow structure is prominent in many rhyo lites and they are often more or less cellular. Spherulites are prominent feature of some rhyolites. They vary from microscopi size to very large dimensions. Rhyolites are usually light colore but may be dark red or even black at times.

Except for the fact that they contain more or less glass, th rhyolites have about the same constituents as the granites. Th quartz, orthoclase, and biotite occur in part in well-forme crystals called phenocrysts. The quartz crystals have a bipy ramidal habit (see Fig. 419, p. 259) different from that of vei quartz (Figs. 416–8). In fact it is, or rather was at the time o its formation, a different kind of silica known as β-quartz, but o cooling it changes to ordinary or α-quartz. The orthoclase unaltered occurs in the transparent variety known as sanidin The dense groundmass, which greatly resembles chalcedony proves on microscopic examination to be a mosaic of orthoclas and quartz in a matrix of more or less glass.

The rhyolites proper grade into volcanic glasses, the principa varieties of which are **obsidian** (vitreous luster), **pitchston** (resinous luster), **perlite** (curved fracture), and **pumice** (highl vesicular). Some of the volcanic glasses contain phenocryst and if these are prominent the rock is called a **vitrophyre.** A these glasses may correspond to trachytes, andesites, etc., th term rhyolitic, strictly speaking, should be used as a prefi but as a matter of fact the great majority of volcanic glasse have the composition of rhyolite. [For a description of glass se page 413.]

(*b*) **Syenite—Trachyte Series.**

The rocks of this series include all those with dominant alkali feldspar (orthoclase, microcline, or albite) which at the same time lack quartz. The glassy equivalents are also included. The rocks of this group are rare, taken the world over, but they are very interesting as they often contain rare minerals.

Syenite is a grained rock consisting largely of orthoclase or microcline with minor amounts of hornblende, biotite, and pyroxene and also such accessories as titanite, apatite and zircon. Nepheline is often present and if in sufficient quantity the rock is called **nepheline syenite.** The nepheline may be recognized by its greasy luster, absence of cleavage, inferior hardness (it is scratched by a knife blade), and solubility in HCl The nepheline syenites frequently contain sodalite. Some varieties of syenite contain corundum as an original mineral. The origin of the **corundum syenites** may be explained by the fact that the original magma contained an excess of Al_2O_3 over that required for silica, alkalies, and other oxids. After these affinities were satisfied, the excess of Al_2O_3 crystallized out as corundum.

In Arkansas syenite has been used as a building stone. It resists fire better than granite because of the more uniform expansion due to the presence of practically one mineral instead of two minerals with unequal coefficients of expansion.

With increase in the amount of plagioclase and ferromagnesian minerals and decrease in the amount of orthoclase the syenites pass through intermediate rocks known as **monzonites,** which contain approximately equal amounts of alkali feldspar and soda-lime feldspar, into diorites.

In texture the syenites grade through syenite porphyries and trachyte porphyries into trachytes. (Note that this name ends in *-yte* instead of *-ite*).

Trachytes are the porphyritic to felsitic equivalents of the syenites, for they contain practically the same minerals. Quartz is lacking though its polymorph tridymite is occasionally present. The feldspar phenocrysts are largely sanidine, the transparent variety of orthoclase, though plagioclase is sometimes also present.

The fine-grained equivalent of nepheline syenite is called **phonolite,** a rare type of igneous rock. Leucite-bearing trachytes are also known. They are prominent in certain Italian volcanic regions. The fine-grained equivalent of monzonite is called **latite.**

The glassy equivalents of trachytes are rare in comparison with the rhyolitic glasses.

(*c*) **Granodiorite-Dacite Series.**

The rocks of this series are intermediate chemically and mineralogically between the granite-rhyolite series and the diorite-andesite series.

Granodiorite is a grained rock containing both alkali feldspar and lime-soda feldspar together with some quartz and fair amounts of ferromagnesian minerals. As the name implies, it is intermediate between granite and diorite. There is too much quartz for a diorite but not enough for a granite. It is close to a quartz monzonite, another intermediate rock type from which it can be distinguished only by a quanitative analysis. The granodiorites grade through quartz diorites into diorites.

Granodiorites are prominent rocks in the great batholiths of the Western United States, for example in the Sierra Nevada of California.

Dacite. The dense equivalent of granodiorite may for convenience be called dacite, though the term is usually employed for a rock of a little lower silica content, the equivalent of quartz diorite. Dacite can usually be recognized by the presence of phenocrysts of quartz together with those of both orthoclase and plagioclase. Dacites are wide-spread rocks but do not form such large masses as the andesites or rhyolites.

Granodiorite porphyry and dacite porphyry are intermediate in texture between granodiorite and dacite.

(*d*) **Diorite-Andesite Series.**

The diorite-andesite series includes all igneous rocks in which the essential minerals are sodic plagioclase and some ferromagnesian

minerals and their glassy equivalents. They are medio-silicic rocks with silica content of about 55 to 60 per cent.

Diorite is a grained rock with about equal quantities of light and dark colored minerals. The light colored mineral is plagioclase (oligoclase or andesite) and the dark colored minerals usually hornblende, augite, or biotite. Under the diorites are included only those rocks in which the plagioclase is more sodic than Ab_1 An_1. This makes the distinction between diorite and gabbro rest upon the character of the plagioclase. In gabbro the plagioclase is more calcic than Ab_1An_1. This means that the character of the plagioclase in many cases must be determined by optical tests but after some experience the two rock types may often be distinguished megascopically.

Some varieties of diorite contain a little quartz (**quartz diorite**) and thus grade into granodiorite.

Between the diorites and andesites we have diorite porphyries and andesite porphyries, names based purely on differences in texture.

Andesites are dense equivalents of the diorites and so the feldspar is oligoclase or andesine (note that the name of this feldspar ends in *-ine* and the rock name in *-ite*). The ferromagnesian mineral is either biotite, hornblende, hypersthene, or augite. Quartz is typically absent but the rocks between andesite and dacite may contain a little quartz. With increase of orthoclase and decrease of ferromagnesian minerals they pass through latites into trachytes and with increase of lime content of the plagioclase they pass into auganites.

The andesites are prominent and wide spread rocks in both North America and South America. Mt. Shasta in northern California consists largely of andesite.

(*e*) **Gabbro-Auganite Series.**

The gabbro-auganite series includes igneous rocks with calcic plagioclase and some ferromagnesian mineral besides olivine as the essential minerals. The absence of olivine distinguishes this series from the olivine gabbro-basalt series.

Gabbro is here used for an olivine-free grained rock consisting essentially of calcic plagioclase (labradorite or bytownite) and augite, hypersthene, or hornblende.[1] The gabbros are usually coarser grained than diorites and the plagioclase is often altered to the mixture of minerals known as *saussurite*. The pyroxene may be altered to an amphibole called *uralite*.

Varieties rich in hypersthene are called **norite**. With increase in the plagioclase content the gabbros grade into **anorthosites** or labradorite rocks, which are sometimes used as an ornamental stone. With decrease in the plagioclase on the other hand, they pass into the pyroxenites, igneous rock composed essentially of pyroxene. Quartz and orthoclase are present in some gabbros but such types are rare.

With decrease in the size of the mineral grains the gabbros grade through gabbro porphyries into auganite porphyries and auganites.

Auganite. This recently introduced term (A. N. Winchell 1912) is a useful one for the dense equivalent of the olivine-free gabbro. Auganite differs from andesite in the fact that the plagioclase is more calcic than $Ab_1 An_1$, and from basalt in the fact that olivine is lacking. It has usually been called augite andesite or olivine-free basalt, but the first name may be used for augite-bearing rocks with sodic plagioclase, and the name basalt may then be restricted to olivine-bearing rocks.

Leucite and nepheline occur in certain rare rocks of this group. One type, leucite tephrite, is abundant in certain parts of Italy.

(*f*) **Olivine Gabbro-Basalt Series.**

The olivine gabbro-basalt series includes igneous rocks with calcic plagioclase, olivine, and some other ferromagnesian minerals as the essential constituents. They contain less silica than the rocks of the gabbro-auganite series on account of the presence of olivine $\{(Mg,Fe)_2SiO_4$; SiO_2 = about 40 per cent.$\}$.

[1] The distinction between diorite and gabbro is based upon the character of the plagioclase rather than upon the ferromagnesian mineral for it is known that in many subsilicic rocks hornblende has been formed from pyroxene at a late magmatic period.

Olivine Gabbro is a grained rock consisting essentially of labradorite (or bytownite) with olivine and either augite, hypersthene, or hornblende. It differs from gabbro proper in the presence of olivine and should have a distinctive name as it belongs to a distinct series and is not, as the name implies, simply a variety of gabbro.

With increase in the amount of olivine and decrease in plagioclase, gabbros grade into peridotites. With increase of the pyroxene and decrease of the other minerals they grade into the pyroxenites. Pyroxene, on the other hand, is practically absent in some varieties; these plagioclase-olivine rocks are called troctolites.

Diabase. This name is used for a common rock type in this series which is characterized by a peculiar texture. The plagioclase occurs in lath-shaped crystals in the interstices of which the augite (and olivine) has formed, presumably at a later period. Ilmenite is a characteristic mineral of diabase and in some diabases analcite occurs as an original mineral.

The diabases usually occur in the smaller intrusions and are thus intermediate in mode of occurrence between the subjacent gabbros and the volcanic basalts.

Basalts are dense igneous rocks with calcic plagioclase (usually labradorite), olivine, and either augite or hornblende as essential minerals. The recognition of auganite as a distinct rock type restricts the term basalt to olivine-bearing rocks. The texture of basalt usually varies from felsitic to subporphyritic. Phenocrysts are rare as compared with those in corresponding rocks in the other series. Vesicular and amygdaloidal basalts are common. Zeolites are especially characteristic, but calcite, quartz, chalcedony, epidote, and chlorite are also frequently present. Amygdaloidal basalts furnish part of the native copper mined in the Upper Peninsula of Michigan.

Basalts are as a rule black or very dark gray but color alone is not a safe distinction.

The basalts usually contain some interstitial glass mixed with fine magnetite dust and thus grade into basaltic glasses,

which are often found as thin crusts on basalt flows or as narrow bands on the sides of basalt dikes.

Nepheline and leucite occur in some rare types of basaltic rocks called basanite.

(*g*) Peridotite-Limburgite Series.

The peridotite-limburgite series includes feldspar-free igneous rocks with olivine and pyroxene as essential constituents with their glassy equivalents. They are very low in silica and alumina and consequently high in lime, magnesia, and iron oxids.

Peridotites are grained rocks with olivine and pyroxene, but with little or no plagioclase. They grade into olivine gabbros on the one hand and into nearly pure olivine rocks (**dunites**) or nearly pure pyroxene rocks (**pyroxenites**) on the other hand. The pyroxene of peridotite may be augite, hypersthene, or enstatite, often an intergrowth of two of them. Hornblende is sometimes present. Common associated minerals are magnetite, ilmenite, chromite, and pyrrhotite. Garnet, spinel, and native iron are also found in peridotites.

Peridotites are seldom found in an unaltered condition but their alteration products, the hydrothermal metamorphic rocks known as serpentine, are very common. The principal mineral of serpentine is antigorite formed at the expense of the olivine and pyroxene of the original peridotite.

The peridotites are usually found in dikes rather than in subjacent rock masses. This is one reason why the petrographic classification of igneous rocks should be based upon texture rather than upon geological occurrence.

Limburgite, the dense equivalent of peridotite, is a very rare rock type and is mentioned here simply for the sake of completeness. It has been called magma-basalt. But the term basalt should be restricted to olivine-plagioclase-augite rocks. The limburgites contain phenocrysts of olivine and augite in a glassy ground-mass. **Augitite** is used for the corresponding rock with augite alone.

OTHER FELDSPAR-FREE IGNEOUS ROCKS

Other feldspar-free rocks include some rare types in which the feldspathoids, nepheline and leucite, take the place of the feldspars. The leucitites, as the dense leucite-pyroxene rocks are called, are abundant in Italy.

There are also rock masses with large amounts of magnetite and ilmenite which are often considered as ultrabasic igneous rocks. A rock of this character occurs at Cumberland Hill, Rhode Island. It contains magnetite, ilmenite, olivine, and plagioclase. The silica content is only 22 per cent., while the combined iron oxids reach as high as 43 per cent.

2. VOLCANIC EMANATIONS

It is a well-known fact that volcanoes emit gases along with lava and fragmental products. Of these gases the principal one is water vapor or steam. Others include hydrogen, oxygen, nitrogen, hydrogen sulfid, sulfur dioxid, carbon dioxid, hydrochloric acid, etc. The openings through which the gases issue are called fumaroles.

In contrast with the prominence of dissolved gases in deep-seated igneous rocks, the gases in volcanic rocks escape and so as a rule they play a comparatively small rôle.

Under favorable conditions, however, volcanic sublimates may form. The principal minerals that appear as volcanic sublimates are: sulfur, sal-ammoniac (NH_4Cl), halite, sylvite, hematite, tenorite (crystalline CuO), covellite, sassolite (H_3BO_3), gypsum, and hornblende.

It is probable that the high-temperature forms of silica, tridymite and cristobalite, are formed by volcanic gases.

3. PEGMATITES

Closely related to plutonic igneous rocks and grading into the high-temperature veins are the rocks known as pegmatites. They occur in relatively narrow dikes or veins and have been formed during the last stages in the consolidation of subjacent

rocks. They are supposed to be due to the crystallization of a sort of mother liquor left after the main rock has consolidated. Mineralizers or dissolved gases probably account for many of the peculiar features of pegmatites. They are coarse grained and are often characterized by the presence of very large crystals. Immense muscovite, feldspar, beryl, and spodumene crystals sometimes occur in them. At one locality in the Black Hills, South Dakota, spodumene crystals up to a length of 14 meters were found. These are the largest crystals on record. Other characteristics of pegmatites are the simultaneous crystallization of two or more minerals such as graphic granite (quartz and feldspar) and perthite (microcline and albite), the variability in texture in different parts of the vein, and the presence of rare elements and rare minerals.

There are pegmatites corresponding to most of the known grained rocks but the granite pegmatites are especially common and the term pegmatite without any qualification usually refers to granite pegmatites. They are very prominent in New England, South Dakota, and southern California. The following minerals are found in granite pegmatites: quartz (both α-quartz and β-quartz, so that the temperature of formation was probably in the neighborhood of 575°C.), microcline (the common feldspar of pegmatites), orthoclase, albite, muscovite, lepidolite, tourmaline, amblygonite [$(Li,Al)(F,OH)PO_4$], topaz, beryl, apatite, fluorite, columbite, garnet, andalusite, and also many rare minerals containing such elements as cæsium, zirconium, uranium, tantalum, etc.

In southern Norway over 70 minerals, most of them very rare, have been found in the syenite and nepheline syenite pegmatites of that region.

4. PYROCLASTIC ROCKS

The pyroclastic rocks are the fragmental products of igneous activity and their consolidated equivalents. They form a connecting link between volcanic igneous rocks, with which they are

usually associated, and sedimentary rocks of mechanical origin. A volcanic ash worked over by water may form a tuffaceous sandstone.

The pyroclasts are formed during the explosive activity of volcanoes and thus these materials are often found interbedded with lavas. The fragments may vary in size from very large **volcanic bombs** through **lapilli** (from a few cms. to a few mms. in size) and so-called **volcanic ash** down to the extremely fine material known as **volcanic dust,** so fine that it floats in the atmosphere for hours or even days before it settles.

Consolidated volcanic ash is called **tuff** and consolidated rock of coarser fragments, **agglomerate.** Tuffs and agglomerates are common in volcanic regions. The older tuffs are firmly consolidated and on account of alteration often may be distinguished only with difficulty.

Except for their fragmental character pyroclasts resemble dense igneous rocks. Many of them, however, consist largely of glass, often the pumice variety. Phenocrysts are common and rock fragments, *i.e.*, composite fragments of two or more minerals or minerals and glass, are very characteristic.

In chemical composition and mineral components the pyroclastic rocks correspond to any of the volcanic or dense rocks. Thus we have rhyolitic tuff, andesitic tuff, etc.

5. SEDIMENTARY ROCKS

Sedimentary rock is a convenient collective term for stratified rock laid down for the most part under water. In some of the sedimentary rocks wind action may have been prominent. The sedimentary rocks may be grouped under three main heads: those of (1) mechanical origin, (2) organic origin, and (3) chemical origin.

(*a*) Sedimentary Rocks of Mechanical Origin.

These rocks are usually stratified. They are derived from pre-existing rocks by mechanical agents. Their concentration

has been preceded by **weathering,** a term used for superficial changes brought about by atmospheric agents and meteoric water. The agents effective in weathering are in part chemical and in part physical. The chemical changes involved are mainly oxidation, carbonation, and hydration. Comparatively few minerals are produced by the weathering of the ordinary rock-forming silicates. The principal ones are limonite, turyite, cliachite, gibbsite, kaolinite, and halloysite. The tendency of weathering is toward simplification. Most of the minerals present in weathered rocks are residual minerals left over from an early stage. The importance of weathering is probably over-emphasized, for some of the effects ascribed to weathering are due to hydrothermal metamorphism. Weathering obviously depends upon climatic conditions. In arid climates it is different from that in humid regions.

Unconsolidated

The coarse unconsolidated material, **gravel,** grades through **sand** into **silt.** The minerals of sand and gravel are largely those that resist wear and chemical action. For this reason quartz is undoubtedly the principal mineral of sand but rarely does the sand or gravel consist entirely of quartz. The common rock-forming minerals such as feldspar and mica are also found in sands and in favorable places where there has been natural concentration we have heavy minerals such as magnetite, ilmenite, garnet, zircon, rutile, tourmaline, and occasionally diamond, gold, platinum, and cassiterite. Locally almost any mineral may occur. For example, on the Hawaiian beaches olivine is the only common mineral of the sand. In the arid regions of certain parts of New Mexico and Utah the dune sands are made up entirely of grains of gypsum. On the island of Ceylon there are found gem-bearing gravels with such minerals as spinel, corundum, garnet, zircon, ilmenite, monazite $(Ce,La,Di)PO_4$, and chrysoberyl $(BeAl_2O_4)$.

Consolidated

Breccia. A rock made up of coarse angular fragments is known as a breccia. The fragments may be quartz, chalcedony, calcite, or almost any mineral or even rock fragments. The cementing material may be the same as, or different from, the fragments.

Conglomerate. Breccias grade into conglomerates, the fragments of which are sub-angular to rounded and are due to mechanical wear. The pebbles of conglomerates usually have been transported considerable distances, while the angular fragments of breccias have been cemented before much mechanical action took place.

Sandstones. Consolidated sands are called sandstones. The grains are subangular to rounded. The principal constituent of sandstone is quartz, but other minerals such as feldspar, muscovite, and calcite are not rare. A sandstone with appreciable amounts of feldspar is known as **arkose.** Closely related to arkose but containing in addition to quartz and feldspar miscellaneous minerals and rock fragments such as bits of shale is the rock known as **graywacke.** It is a kind of fine-grained conglomerate. According to the character of the cementing material sandstones are classed as calcareous, ferruginous, siliceous, or bituminous. On account of porosity fossils are comparatively rare in sandstones. The calcite in calcareous sandstones is due in part to a recrystallization of the calcium carbonate of calcareous fossils. Loosely cemented sandstones with grains of glauconite are called **greensands.** They are used as fertilizers and are also a possible source of potassium salts. Greensands are prominent in the Cretaceous of New Jersey.

With increasing fineness of grain sandstones pass into shales. With increase in the amount of calcite they pass into limestone. There are also gradations between sandstones and tuffs (tuffaceous sandstone) and between sandstones and quartzites (quartzitic sandstones).

Shales are more or less laminated sedimentary rocks made up largely of indefinite hydrous aluminum silicates. They may also contain quartz and calcite and thus grade on the one hand into sandstones and into limestone on the other. Minerals visible to the unaided eye include pyrite and gypsum. Shales are consolidated muds and clays composed for the most part of the finer materials produced by land waste. Typical shales are of mechanical origin but some of the siliceous rocks of organic origin are also known as shales on account of their laminated character.

Clays are massive, loosely compacted rocks, containing hydrous aluminum silicates (including kaolinite and halloysite) with more or less finely derived quartz, sericite, and sometimes feldspar and other possible minerals. The term clay is often restricted to material that becomes plastic when wet with water.

Some clays are derived from rocks by weathering in place. Besides these residual clays there are also transported clays.

No clear distinction can be drawn between clays and shales. Clays, though, are mainly terrestrial deposits and shales submarine deposits.

Bauxite is a surficial rock consisting largely of amorphous cliachite $[Al_2O_3(H_2O)_x]$ with more or less crystalline gibbsite $(Al_2O_3 \cdot 3H_2O)$. It usually has a pisolitic structure but some varieties greatly resemble ordinary clay. Bauxite, according to recent investigations, is formed by the desilication of clay, which in turn was formed from such igneous rocks as syenite. It is found in Alabama, Tennessee, and Arkansas, and probably was formed under tropical conditions of weathering.

(*b*) Sedimentary Rocks of Organic Origin.

It is a well-known fact that certain organisms secrete calcium carbonate or silica from the waters in which they live in order to build up hard parts (shells or tests) for the support of their soft tissues. In other cases the organic matter of the organism itself is preserved and this accumulated material may form a rock.

Limestone. The most common rock of organic origin is

limestone, which consists almost entirely of the mineral calcite, usually in a massive form. While often apparently amorphous it is really microcrystalline. Calcium carbonate is present in most natural waters and is secreted by various organisms such as molluscs, brachiopods, echinoderms, bryozoa, corals, certain sponges, and some foraminifera. The organisms just named are animals but some plants such as algæ also secrete calcium carbonate. Most of the limestones are marine in origin but fresh water limestones are also known. They may be recognized by the presence of plant stems and fresh water mollusc shells such as those of snails.

When the organisms die, the organic material decays and there remain the shells and tests and other hard parts such as crinoid stems and coral fragments. They accumulate and are more or less broken up, often ground to bits and thus form a calcareous mud which on hardening produces a limestone.

Besides the mineral calcite, sedimentary limestones may contain dolomite, quartz, chalcedony, and such minerals as barite, celestite, anhydrite, gypsum, siderite, aragonite, collophane, and pyrite. These minerals occur for the most part in seams and cavities along with recrystallized calcite.

Varieties of limestone are based in part upon the character of the fossils present, *e.g.*, crinoidal limestone, coral limestone, mummulitic limestone, and shell limestone (the shell limestone on the coast of Florida is called *coquina* and represents the first stage in the formation of some limestone). Chalk is a very fine-grained porous limestone formed by the consolidation of calcareous ooze which is made up principally of tests of foraminifera. Though chalk is apparently amorphous, microscopic examination proves it to be microcrystalline.

Depending upon the impurities present such varieties of limestone as siliceous, arenaceous, argillaceous, and bituminous are recognized. These show gradations toward cherts, sandstones, shales, and hydrocarbons respectively. A limestone that will take a polish, whether sedimentary or metamorphic, is called marble.

The name limestone is not restricted to sedimentary rocks of organic origin but is used for any massive rock made up largely of calcite. Thus we have oölitic limestones of chemical origin and crystalline limestones of metamorphic origin.

Diatomite or Diatomaceous Earth. Although most organisms secrete calcium carbonate some secrete silica in the form of opal. Among animals these include sponges and radiolaria and among plants, diatoms. Siliceous deposits are forming in the ocean at the present time. Thus we have radiolarian ooze and diatomaceous ooze produced by the sinking of the tests of radiolaria and diatoms from near the surface of the sea to the bottom. There are also calcareous oozes (globigerina ooze) and argillaceous deposits known as "red clay."

The consolidation of these oozes after the uplift of the sea furnishes diatomite or diatomaceous earth, in which there are found not only diatoms but also radiolaria and sponge spicules, usually in a fragmentary condition. These deposits are mostly Tertiary in age and are abundant in the Western United States. A very large deposit is now being quarried near Lompoc, Santa Barbara county, California. When these deposits become more or less laminated and mixed with detrital material they are known as siliceous shale. It is possible that some of the older cherts are of organic origin, but most of them are now believed to have been formed by the replacement of limestones or shales by silica.

Carbonaceous Rocks. To make the classification of the organically-derived rocks complete we must include carbonaceous rocks such as coal. While coal is not a mineral it may be considered a mineraloid (see page 413). Coal is a sedimentary rock occurring interbedded with shales and sandstones. If is of plant origin, for not only may plant tissues be recognized in thin sections and polished surfaces, but an almost perfect gradation may be traced from peat through lignite to the various types of coal such as sub-bituminous, bituminous, and semi-bituminous into semi-anthracite and anthracite. Anthracite may be considered a special type of metamorphic rock.

Coal consists largely of three elements: carbon, hydrogen, and oxygen, with smaller amounts of nitrogen and sulfur. Analyses, however, are usually given in the form of proximate constituents, which include moisture, volatile hydrocarbons, fixed carbon, and ash. Anthracite is highest in fixed carbon and lowest in ash, while lignite is lowest in fixed carbon and highest in moisture.

The associated minerals of coal include pyrite, marcasite, gypsum, dolomite, melanterite ($FeSO_4 \cdot 7H_2O$), and copiapite (basic ferric sulfate).

Other Deposits of Organic Orgin.

In addition to calcite, opal, and hydrocarbons, certain other minerals are believed to be have been formed at times by organic agencies. Among them are sulfur and limonite.

Collophane is also in part of organic origin. The bones of vertebrate animals consist of calcium carbonophosphate together with an organic substance called ossein. The organic matter is gradually eliminated and its place is taken by the calcium carbonophosphate from the solution of other bones. Sometimes bones accumulate and form *bone-breccias*. The cementing material of the bone fragments is calcite and there may be partial replacement of the collophane by calcite.

Most of the phosphorites or so-called phosphate rocks seem to have been formed by the replacement of limestones by collophane.

(*c*) Sedimentary Rocks of Chemical Origin.

In this division are placed those rocks which have been formed by the evaporation of inland bodies of water or those that have been formed by the replacement of mechanical or organic sediments by solutions. Replacement deposits of hydrothermal origin are discussed under metamorphic rocks. Rocks of this group are perhaps not as common as the two preceding divisions but they are fully as important for they include many deposits of economic value.

Gypsum is a rock as well as a mineral. It occurs in thick massive beds associated with shales and limestones and owes its

origin in many cases to the evaporation of inland seas. Hence it is often associated with saline deposits. Among the minerals it may contain are calcite, dolomite, celestite, sulfur, and quartz.

Anhydrite, both as a mineral and as a rock, is a frequent associate of gypsum, and it has been proved that some gypsum deposits have been formed by the hydration of anhydrite.

Secondary deposits of gypsum in an impure and loosely compacted form are known as **gypsite** or gypsum earth.

Gypsum as a rock is found in New York, Michigan, Iowa, Kansas, Oklahoma, New Mexico, and other states.

Anhydrite like gypsum occurs as a rock as well as a mineral. It occurs in beds and even more frequently than gypsum it is associated with saline deposits. The reason for this is as follows: sea-water on evaporation first yields hydrous calcium sulfate (gypsum), then when the solution becomes sufficiently high in sodium chlorid, anhydrous calcium sulfate (anhydrite) forms and soon afterwards sodium chlorid (halite) is deposited; so that in many salt mines an anhydrite bed is found directly below the bed of rock-salt.

The minerals associated with anhydrite include, besides halite, dolomite, calcite, quartz, and gypsum. Near the surface anhydrite is usually converted into gypsum and many gypsum beds have thus been formed.

Anhydrite rocks are found in Michigan, Kansas, Oklahoma, Texas, and Nevada. It is a prominent rock in the Stassfurt (Prussia) salt deposits.

Rock-salt. Halite or sodium chlorid often occurs in thick beds and hence must be classed as a rock. It is formed by the evaporation of sea-water in enclosed bays or inland seas after calcium sulfate has been deposited. Overlying shales or clays are necessary to protect the bed of rock-salt from solution unless the region is an excessively arid one. Anhydrite is probably the most commonly associated mineral but the chlorids and sulfates of potassium and magnesium also occur. Of these the most important is sylvite (KCl). Strange to say, halite and sylvite

occur side by side and do not form an isomorphous mixture as one would expect.

Rock-salt is found in nearly all parts of the world and in beds that were deposited in practically all the geological periods.

Other Saline Deposits. Sea-water also contains potassium and magnesium and when the evaporation is complete salts of these metals will crystallize out. This has happened in a few cases and the deposits thus formed have been protected from solution by overlying clays.

The important minerals of these deposits are: sylvite (KCl), carnallite ($KMgCl_3 \cdot 6H_2O$), kainite ($KMgCl(SO_4) \cdot 3H_2O$), kieserite ($MgSO_4 \cdot H_2O$), and polyhalite ($K_2MgCa_2(SO_4)_4 \cdot 2H_2O$) in addition to halite. Of these kainite and sylvite are said to be secondary minerals, that is they have been formed at the expense of the others (primary) after they were deposited in beds.

At Stassfurt, Prussia, the deposits of the above-mentioned minerals are of great commercial importance, as are also the more recently discovered potash deposits near Mulhouse, Alsace, where sylvite and halite occur together in immense beds. Another commercial deposit is at Suria in Catalonia (Spain), where sylvite and carnallite occur in deposits of Tertiary age.

Soda Lake Deposits. Although these deposits are not usually considered rocks they deserve notice at this place. Sodium carbonate, sodium borate, and sodium sulfate as well as sodium chlorid occur as the result of the evaporation of lakes in arid regions. These lake deposits are found in Wyoming, Nevada, and California. The principal minerals are trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), mirabilite ($Na_2SO_4 \cdot 10H_2O$), thenardite ($Na_2SO_4$), gaylussite ($Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$), pirssonite ($Na_2CO_3 \cdot CaCO_3 \cdot 2H_2O$), epsomite ($MgSO_4 \cdot 7H_2O$), glauberite ($Na_2SO_4 \cdot CaSO_4$), hanksite ($9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$), borax ($Na_2B_4O_7 \cdot 10H_2O$), and ulexite ($NaCaBO_{59} \cdot 8H_2O$).

Nitrate Deposits. Extensive deposits of nitratine ($NaNO_3$) are found in the arid regions of northern Chile in superficial beds up to two meters in thickness. The associated minerals are halite, gypsum, and lautarite [$Ca(IO_3)_2$].

Oölitic limestone. A variety of limestone made up of minute spherical concretions resembling fish roe and known as oölitic limestone is common in the Pennsylvanian of the Middle West and in the Jurassic of England. Along the shores of the Great Salt Lake of Utah an oölitic sand now forming evidently represents the first stage in the production of oölitic limestone.

Most other oölitic rocks seem to have been derived from oölitic limestones by replacing solutions, but the oölitic phosphorite of southeastern Idaho is probably a chemically formed deposit formed by the direct deposition of collophane.

Travertine. Calcium carbonate is soluble in carbonated water and on the escape of the carbon dioxid due to release of pressure, calcium carbonate is deposited in the form of calcite or more rarely in the form of aragonite. It is this process that accounts for certain calcareous deposits, the banded ones of which are called travertine. Some of these are spring deposits and some are cave deposits closely related to the familiar stalactites and stalagmites.

Calcareous tufa. A more or less porous calcareous deposit formed by springs is known as calcareous tufa. (Tufa should be distinguished from tuff, a fragmental volcanic rock). The calcareous tufas often show remains of mosses. Aquatic plants like terrestial ones require carbon dioxid for their existence and so when the carbon dioxid is extracted from the water by the plant the calcium carbonate is precipitated. The deposit then is in part of indirect organic organ. This example shows the impossibility of establishing a satisfactory classification of rocks for there is no exact dividing line between the organic and chemical deposits. Some of the calcareous tufas are lake deposits, for example, those in the Great Basin region of Nevada.

Other limestones of organic origin. All limestones are not of organic origin. It seems probable that calcium carbonate may be deposited from solution under certain conditions not including those mentioned above.

Thus the limestone occurring at Green River, Wyoming, was

formed in brackish water. This is known from the character of the fossil fish present.

Siliceous sinter. Silica in the form of opal is deposited from hot springs, as for example, Yellowstone National Park. The rock is called geyserite. Algæ living in the hot water secrete silica and thus the deposits grade into the organically-formed rocks.

Ice. To be complete, ice should be mentioned here. Ice is a rock as well as a mineral of especial prominence in the polar regions.

Rocks formed by replacement of limestone. Most of the sedimentary rocks made up of dolomite, chalcedony, and collophane seem to have been formed by the replacement of limestone. These rocks, however, can hardly be called metamorphic for the replacement was brought about by sea-water or by percolating meteoric waters and not by ascending hydrothermal solutions.

Dolomitic limestone is a sedimentary rock made up largely of the mineral dolomite with more or less calcite. There is good evidence to show that the majority of dolomitic limestones were formed from ordinary limestones while they were still under the sea. This process, which consists in the removal of part of the calcium and the substitution of magnesium in its place, is called **dolomitization.** But in some cases dolomitic limestones have been formed by the replacement of limestone after it was uplifted above the sea, sometimes by the agency of meteoric waters and sometimes by hydrothermal solution in connection with ore deposition.

Chert. Most of the compact massive rocks made up largely of chalcedony and known as chert or flint were probably formed by the replacement of limestones or shales by means of siliceous solutions. Although radiolaria, diatoms, and sponge spicules doubtless have contributed their share of silica, most of the fossils present in cherts were originally calcareous. Some of the cherts, however, may have been formed from radiolarian ooze.

Phosphorite or so-called phosphate rock is a sedimentary rock composed largely of the amorphous mineral collophane, a calcium carbonate-phosphate. The associated minerals include dahllite (the crystalline equivalent of collophane), calcite, fluorite, gypsum, chalcedony, and quartz. Although the phosphatic material is in part of organic origin, most of the phosphorites seem to be replacement of limestones as fossils present were originally calcareous.

The high-grade phosphorites are used extensively as a source of calcium superphosphate, which is employed as a fertilizer. They occur in Florida, Tennessee, and also in southeastern Idaho and the adjoining portions of Wyoming and Utah.

6. METAMORPHIC ROCKS

The third great group of rocks consists of those which though originally either igneous or sedimentary now possess characters that entitle them to recognition as a separate group. New minerals or new textures or both have been developed by geologic agents such as heat, pressure, or hydrothermal solutions. The term **metamorphism,** though sometimes used in a broad sense for practically all rocks except the igneous, is generally restricted to changes brought about by hypogene or deep-seated forces acting from within the earth's crust or outer shell. Used in this sense metamorphism excludes weathering and the replacement of sedimentary rocks by solutions of meteoric water.

A number of minerals such as antigorite, talc, chlorite, tremolite, kyanite, sillimanite, staurolite, graphite, diopside, forsterite, chondrodite, phlogopite, vesuvianite, glaucophane, and wollastonite are highly characteristic of metamorphic rocks.

Most of the metamorphic rocks have a foliated or laminated structure but some of them lack this and are massive.

No satisfactory classification of the metamorphic rocks has yet been devised. Some of the names used are based upon chemical composition and some upon structure. They may be discussed conveniently under three great heads: rocks produced by

regional, contact, and hydrothermal metamorphism, the chief agents of which are pressure, heat, and hot solutions respectively.

(*a*) **Regional Metamorphism.**

Gneiss is a coarsely laminated metamorphic rock of a great variety of mineral components. The term usually is used in a purely structural or textural sense. Most gneisses are recrystallized igneous rocks and hence feldspars are usually present. Other minerals include quartz, muscovite, biotite, muscovite, hornblende, glaucophane, epidote, chlorite, sillimanite, and garnet.

Varietal names for gneisses are derived (1) from a prominent mineral present, *e.g.*, biotite gneiss, and (2) from the original rock that produced the gneiss, *e.g.*, granite gneiss. Some of the gneisses are derived from sedimentary rocks such as conglomerates. The chemical analysis may sometimes be used to distinguish a sedimentary gneiss from an igneous gneiss.

No exact dividing line can be drawn between gneiss proper and the banded gneissoid igneous rocks in which the banding is believed to be original. With increasing fineness of texture the gneisses grade into schists.

Schists are finely laminated metamorphic rocks intermediate in texture between the gneisses and the slates and of almost any composition. Varietal names are based upon prominent minerals present. Thus we recognize mica schist, hornblende schist, talc schist, graphite schist, etc. The micas (muscovite, biotite, and sericite) are probably the most conspicuous minerals. Feldspars are usually absent and in cases of doubt their presence or absence may help to decide whether to call the rock gneiss or schist. Garnet is a common mineral and such minerals as staurolite, kyanite, andalusite, sillimanite, epidote, glaucophane, and tourmaline are frequently found.

Most of the common varieties of schists have been formed from sedimentary rocks but some of them were originally igneous rocks.

Slates. The mica schists grade into the slates, which are

argillaceous metamorphic rocks characterized by extremely well developed rock cleavage. The material of slate seems to be largely sericite in very minute scales, but visible minerals include pyrite, calcite, and dolomite. The coloring matter is usually carbonaceous matter (black), chlorite (green), or iron oxide (red).

The slates with an even, persistent rock cleavage are used for roofing purposes, but the great majority of slates have no economic value.

Quartzites are the metamorphic equivalents of sandstones and may be distinguished from the latter by the fact that the fracture takes place through quartz grains and cement alike, so firmly has the rock been cemented. Quartz and chalcedony are the principal minerals but feldspars, sericite, chlorite, kyanite, and other silicates are sometimes present. The quartz often shows secondary enlargement of the original sand grains when examined in thin sections. The later deposited quartz then appears in optical continuity with the original grains of quartz.

Quartzites grade through schistose quartzites into quartz schists and through quartzitic sandstones into ordinary sandstones.

Some of the quartzites are simply local occurrences of hardened sandstones and are not, properly speaking, metamorphic rocks. This is another example of the unsatisfactory nature of rock classification.

Quartzites are used for paving blocks and for the manufacture of silica bricks.

Crystalline limestones are metamorphosed sedimentary limestones The term crystalline is used in an arbitrary way, for all limestones are made up of crystalline calcite. The crystalline limestones are sometimes called marble but the latter term is preferably used for any limestone that will take a polish and can be used commercially, whether it is sedimentary or metamorphic.

If the original sedimentary limestone were pure the result of metamorphism is simply recrystallization and the resulting

product may be fine-, medium-, or coarse-grained. Schistose structures are rarely developed in limestone on account of the peculiar behavior of calcite under pressure. Under pressure calcite crystals undergo gliding, which is a slipping of adjacent layers on each other along crystallographic directions. In calcite the gliding plane is the negative rhombohedron e $\{01\bar{1}2\}$. The gliding relieves the strains and there is little or no parallel arrangement of the calcite grains. In case the original limestone contained impurities such as clay and sand, recystallization develops such silicate minerals as diopside, tremolite, garnet, vesuvianite, etc. Graphite is also very common and is formed from organic matter.

Crystalline dolomitic limestones are formed by the recrystallization of sedimentary dolomitic limestones. They consist largely of dolomite and calcite. Other minerals present are graphite, spinel, phlogopite, forsterite, chondrodite, etc. The rocks that contain the magnesium silicates in appreciable amounts contain calcite and little or no dolomite. During metamorphism the magnesium seems to have a greater affinity for silica and alumina than calcium has. This process is called **dedolomitization,** as it is in some respects the reverse of dolomitization.

(*b*) Contact Metamorphism.

When an igneous intrusion breaks through sedimentary limestone there is often developed a contact zone with silicate minerals. The minerals in the contact zone are due partly to recrystallization of the impurities of the original limestone but there has often been an addition of material from the igneous intrusion itself. For example, andradite, the calcium-iron garnet, is a common mineral in these contact zones and it is practically certain that the iron at least is derived from the intrusive magma as no sedimentary limestone contains such large amounts of iron without a correspondingly large amount of aluminum.

The common minerals of the contact zone include andradite,

grossularite, wollastonite, vesuvianite, diopside, tremolite, scapolite, epidote, tourmaline, forsterite, and rare minerals too numerous to mention, some of which are highly characteristic. The contact metamorphic zones rival the granite pegmatites in number and variety of minerals present.

In these contact zones ore-deposits are often encountered. The prominent ore-minerals are magnetite, hematite, pyrite, pyrrhotite, chalcopyrite, bornite, sphalerite, and molybdenite. The abundance of these minerals in places also points to the probability that the magma furnished most of the iron, copper, sulfur, etc., necessary for the production of these minerals. At a stage later than the contact metamorphism the silicate minerals mentioned above may be converted into such minerals as antigorite, talc, tremolite, chlorite, and sericite and the ore-minerals changed to chalcocite and covellite.

By contact metamorphism argillaceous rocks such as shales may be converted into slates or into the fine-grained metamorphic rock known as **hornfels**. The prominent minerals of hornfels are andalusite, garnet, kyanite, tourmaline, and cordierite.

(*c*) Hydrothermal Metamorphism.

This is the type of metamorphism caused by hot ascending solutions, which are usually alkaline. Some of the mineral aggregates ordinarily called rocks, such as the serpentines for example, are formed by hydrothermal metamorphism but most of the hydrothermal products are found in the altered zones adjacent to ore-bearing veins. Although these altered zones are not usually considered rocks they deserve some attention at this point.

The following minerals are characteristic of hydrothermal metamorphic rocks and zones: quartz, chalcedony, sericite, adularia, albite, chlorite, pyrophyllite, antigorite, talc, calcite, dolomite, siderite, fluorite, barite, tourmaline, biotite, magnetite, muscovite, epidote, tremolite, alunite, topaz, and tourmaline. Of these, tourmaline, muscovite, and topaz are formed at fairly high temperatures and others such as chalcedony and adularia

and probably sericite, tremolite, antigorite, and talc are fairly low-temperature minerals. Associated with the minerals above enumerated we find in greater or less amount the following common ore-minerals: pyrite, chalcopyrite, sphalerite, and galena.

Serpentine. Although hydrothermal processes may play a minor part in the formation of most of the metamorphic rocks, at least one rock type, namely, serpentine, must be placed in the hydrothermal division. Serpentine is here used as the name of a massive metamorphic rock consisting essentially of the mineral antigorite. The minerals associated with antigorite include chrysotile, magnetite, chromite, olivine, and pyroxene. Of these the last three are residual minerals from the original rock. The great majority of serpentines were derived from peridotites and related rocks such as pyroxenites and dunites. The alteration is largely one of hydration but the process is not due to weathering, for the serpentine undergoes still further changes when exposed to the surface. Talc is often associated with antigorite and in some cases at least it has been derived from serpentine by a still further hydrothermal alteration.

Ophicalcite is a transitional rock between crystalline limestone and serpentine. The principal minerals are calcite and antigorite; the antigorite has been formed from forsterite or diopside of a crystalline limestone by hydrothermal metamorphism.

Verde-antique is a related serpentinous rock with white veins of calcite, dolomite, or magnesite.

7. VEINS AND REPLACEMENT DEPOSITS

Under favorable conditions of temperature and hydrostatic pressure practically all inorganic substances are soluble in certain kinds of water. Carbonates are soluble in carbonated water; silica is soluble in hot water containing alkaline carbonates. Veins are formed by the deposition of these or other soluble materials along relatively narrow fissures, usually by ascending solutions. In addition to these **fissure veins,** there are also **replacement veins** formed by the replacement of the

country rock along more or less definite zones. The replacement veins grade into irregular replacement deposits. These are especially common in limestones.

The solutions that produce the greater number of ore-bearing veins are believed to have their origin in a magma, for it is a well-known fact that outside the iron ores and some of the lead and zinc ores most ore-deposits are found in regions of igneous rocks. It is also significant that the associated silicate minerals of veins and replacement deposits are almost exclusively those that are found in altered igneous rocks. No clear distinction can be drawn between replacement deposits and hydrothermal metamorphic deposits.

The principal gangue minerals of veins and replacement deposits are: quartz (α-quartz), chalcedony, calcite, dolomite, siderite, rhodochrosite, barite, fluorite, adularia, albite, tourmaline, and alunite, and more rarely anhydrite, lepidolite, rhodonite, and the zeolites.

The chief ore-minerals associated with these are pyrite, pyrrhotite, marcasite, galena, sphalerite, chalcopyrite, bornite, arsenopyrite, tetrahedrite, enargite, stibnite, cinnabar, gold, argentite, magnetite, hematite, cassiterite, wolframite, molybdenite. There are of course many rare minerals besides these.

Veins and replacement deposits have been grouped by Lindgren under three large divisions (*a*, *b*, *c* below) according to the temperature of formation, which in general depends upon the depth. Certain minerals are more or less characteristic of each of these groups, although α-quartz, calcite, pyrite, chalcopyrite, sphalerite, galena, and gold have a considerable range of temperature and hence are common to all three groups.

(*a*) High-Temperature Deposits. (Temperature 300°–500°C. ±).

The presence of such minerals as tourmaline, garnet, topaz, lepidolite, muscovite, biotite, apatite, magnetite, ilmenite, and cassiterite is an indication that the deposit was formed at considerable depth (since exposed by erosion) under great hydro-

static pressure and at comparatively high temperatures. Among high-temperature deposits may be classed: (1) cassiterite (or tin-stone) veins, (2) wolframite veins, (3) molybdenite veins, (4) certain gold-quartz veins (Juneau region, Alaska), (5) gold tellurid veins of Western Australia, and (6) gold-tourmaline veins of Meadow Lake district, California.

(*b*) **Intermediate-Temperature Deposits (Temperature 150°–300°C.±).**

These are distinguished by the absence of most of the minerals mentioned under (*a*) and instead we have as dominant gangue minerals quartz, calcite, dolomite, siderite, and barite, and as ore-minerals, pyrite (rarely pyrrhotite), chalcopyrite, bornite, galena, arsenopyrite, tetrahedrite, enargite, sphalerite, and gold. Hydrothermal alteration product minerals are usually abundant and include sericite, chlorite, and albite (probably a low temperature form). Among prominent examples of intermediate deposits are the following: (1) gold-quartz veins of California, (2) silver-lead veins of northern Idaho, (3) silver-lead replacements of limestone (Leadville, Colo., Tintic, Utah), (4) silver-cobalt veins of Ontario (Canada), (5) copper veins of Butte, Montana, and (6) pyritic replacements, Shasta County, California.

(*c*) **Low-Temperature Deposits (Temperature 50–150°C.±).**

Certain deposits believed to have been formed comparatively near the surface at relatively low temperature and slight hydrostatic pressure are characterized by the presence of such minerals as adularia, amethyst, quartz, chalcedony, opal, fluorite, alunite, and in a few cases zeolites, in addition to ubiquitous quartz and calcite. The distinctively high-temperature minerals are absent. Of the ore minerals, pyrite, marcasite, cinnabar, and stibnite are typical, though many others occur.

Included in the low temperature deposits are the following: (1) Tertiary gold-quartz veins of Nevada and Idaho, (2) gold tellurid veins of Cripple Creek, Colorado, (3) silver-gold ores of Tonopah, Nevada, (4) gold deposits of Goldfield, Nevada,

(5) mixed ores of the San Juan region, Colorado, (6) cinnabar deposits, and (7) stibnite deposits.

(*d*) **Stages in Mineral Formation.**

While occasionally two minerals may have crystallized out simultaneously as in the case of graphic granite (quartz and orthoclase), the microscopic study of ores in polished surfaces proves that the minerals are formed in stages one after another. Most of the copper deposits show the following succession of ore-minerals: (1) pyrite, (2) chalcopyrite, (3) bornite, (4) chalcocite. This succession is doubtless due to gradual decrease of temperature. In the high-temperature veins we have not only characteristic high-temperature minerals but also lower temperature minerals formed at later stages. It is thus possible in many cases to determine the history of the deposit.

Several more or less distinct periods of deposition brought about by ascending solutions may often be recognized, but still more striking are the results brought about by descending solutions.

(*e*) **Ore-Deposits not Related to Igneous Intrusions.**

The three clases of deposits mentioned above are believed to have had a genetic connection with igneous rocks. In other classes of ore-deposits there seems to be no possible connection with igneous intrusions and so they are believed to have been formed by meteoric waters. As many of these minerals are sulfids, the solutions that deposited them are supposed to have been alkaline; hence an artesian circulation is postulated.

Good examples of such deposits are the lead and zinc ores of the Joplin district of southwestern Missouri and adjoining portions of Kansas and Oklahoma. The principal gangue minerals are chalcedony (very little quartz is present), dolomite, and calcite and the ore-minerals are sphalerite, galena, marcasite, and pyrite with a very little chalcopyrite. The silicates of hydrothermal deposits are entirely absent and there are no igneous rocks of any kind in the region.

The copper ore of the "Red-beds" type found in New Mexico, Texas, Oklahoma, and other western states is another good example of this class. Nodules and wood replacements in sandstones and shales contain varying amounts of chalcopyrite, bornite, chalcocite, and covellite in addition to pyrite and hematite. Polished surfaces of wood replacements show cell-structure under the microscope.

(*f*) **Zone of Oxidation.**

Most of the vein minerals mentioned under (*a*), (*b*), (*c*) above are unstable when subject to weathering processes which become active when the deposits are exposed by erosion. By means of meteoric water carrying oxygen the sulfids are changed first to sulfates and then to oxids or hydroxids. The exposed oxidized portion of a vein or replacement deposit is called the **gossan** or "iron-hat." At the surface a more or less cellular rusty outcrop of quartz occurs. This is the leached zone. The oxidized zone usually continues for some distance below this leached material and in its lower portion often contains oxids, carbonates, or sulfates.

The following are some of the characteristic minerals of the oxidized zone listed according to metallic content:

Iron. Limonite, goethite, hematite, turyite, copiapite ($Fe_4(OH)_2(SO_4)_5 \cdot 17H_2O$), melanterite ($FeSO_4 \cdot 7H_2O$), and jarosite.

Copper. Cuprite, melaconite ($CuO(H_2O)_x$), copper, malachite, azurite, chalcanthite, brochantite, atacamite ($Cu_2(OH)_3Cl$), olivenite ($Cu_2(OH)AsO_4$), and chrysocolla.

Zinc. Smithsonite, calamine, hydrozincite ($Zn_3(OH)_4CO_3$), and goslarite ($ZnSO_4 \cdot 7H_2O$).

Lead. Cerussite, anglesite, pyromorphite, mimetite, vanadinite, and wulfenite.

Manganese. Psilomelane, pyrolusite, and manganite.

Silver. Silver (also original) and cerargyrite.

Mercury. Mercury (Hg) and calomel (Hg_2Cl_2).

Cobalt. Erthyrite ($Co_3(AsO_4)_2 \cdot 8H_2O$).

Nickel. Annabergite ($Ni_3(AsO_4)_2 \cdot 8H_2O$).

Antimony. Stibiconite.

Molybdenum. Molybdite ($FeMoO_4 \cdot 7H_2O$) and powellite ($CaMoO_4$).

(*g*) Supergene Enrichment.

Very often, especially in copper mines, there is found below the oxidized zone and above the original zone of sulfids an enriched zone usually called the zone of secondary sulfid enrichment. This was first recognized by American mining geologists in 1900.

In the case of copper deposits the prominent minerals of this zone are chalcocite and covellite. These have been formed by the action of soluble sulfates produced by the oxidation of sulfids, principally pyrite, upon the unaltered sulfids below such as pyrite and chalcopyrite. Polished surfaces of the ore show areas or spots of pyrite, chalcopyrite, or bornite bordered by rims, or penetrated by veinlets, of chalcocite or covellite. Oxidation products such as limonite, cuprite, melaconite (CuO), (H_2O)$_x$) malachite, brochantite, or chrysocolla may also be present, but these have been formed at a later period.

Although much of the chalcocite is formed by meteoric waters some investigators, among them the author, believe that in the case of certain deposits such as those of Butte, Montana, (where the chalcocite is found at depths of over 3000 ft.) much of the chalcocite is formed by ascending solutions. This now seems certain in the light of the recent discovery (Schneiderhöhn, 1920) that some chalcocite was evidently formed above 91°C., as it is a paramorph of β-Cu_2S (formed below 91°C.) after α-Cu_2S (formed above 91°C.).

It is usual for geologists and mining engineers to call minerals or ores formed by ascending solutions "primary" and those formed by descending solutions "secondary." This, however, is not the original use of these terms. A primary mineral is an original mineral and a secondary mineral is one that is formed

subsequently. The ambiguity in the use of these words may be avoided by the use of the terms hypogene and supergene introduced by Ransome. A **hypogene** ore or mineral is one formed by ascending solutions, while a **supergene** ore or mineral is one formed by descending solutions. The terms primary and secondary may then be used in their original, mineralogical sense.

Hypogene and supergene chalcocite may usually be distinguished by a careful microscopic examination of polished surfaces.

PART IV

THE DETERMINATION OF MINERALS

The great majority of mineral specimens may be recognized after careful inspection, but such sight recognition requires considerable experience and until one has gained this experience by handling and testing many minerals he must use physical and chemical tests in determining the mineral. If there is no clue to the mineral, it is better to use determinative tables than to make tests at random. Two tables have been prepared for this purpose. Table I makes use of physical tests, structure, and crystal form, and so may be employed in the field. Table II makes use of chemical and blowpipe tests with physical tests used as confirmatory tests. Its use is of course limited to the laboratory and as minerals do not always show characteristic crystal form, structure, color, etc., it is of more general application than Table I.

It should be emphasized that these or similar tables do not determine a mineral, but simply aid one in the determination. The description of the suspected mineral should always be consulted and additional confirmatory tests made. If this is not done the use of the tables becomes mechanical and no progress is made.

The very common minerals are given in capitals. They should be considered first, for most of the minerals found are the common ones. There is also a chance that the mineral specimen one attempts to determine is not included in the list of 175 treated in this book. If the mineral does not agree with any given in this book, then it may be well to consult a larger book such as Brush and Penfield's *Determinative Mineralogy and Blowpipe Analysis.*

Remarks on the Use of Table I. In Table I the first division is based upon crystal form. Crystal form is highly characteristic and many minerals may be distinguished by crystal form alone. A hand lens (a triple aplanat with focus of about 18 mm. is recommended) will be found very useful in examining small crystals. The simple reflection goniometer described on p. 59 may be used to advantage in determining a mineral by its crystal form. It should be noted that isomorphous minerals, such as barite and celestite, have nearly identical interfacial angles; also that for all isometric crystals the angles between corresponding faces are identical.

On account of its constancy, cleavage is one of the best means of identifying minerals. Cleavage should be recognized by step-like surfaces rather than by cracks as these may be due to other causes.

The minerals with metallic luster are quite constant in color provided a fresh fracture is used. For some non-metallic minerals the color is characteristic and practically constant but for others there is great variation.

The specific gravity is one of the most constant properties of minerals and for pure massive specimens without cleavage or structure it is one of the best means of identification. In divisions *B*, *C*, and *D* of Table I the minerals in each subdivision are arranged according to increasing specific gravity. On p. 150 will be found a list of the minerals treated in this book arranged according to specific gravity.

Remarks on the Use of Table II

In table II the important tests are blowpipe and wet tests and so the homogeneity and purity of the mineral are important. All the tests must of course be made of the same kind of material. If possible the impurity should be removed, if not, its effect must be taken into account. One mineral often may be removed from another by means of a magnet, by panning, by specific gravity separation in a heavy solution, or by treatment with dilute

acid in case one of them is insoluble. The homogeneity cannot always be judged by inspection even with the hand lens. It is often necessary to examine the specimen in thin sections or fragments to see whether or not it is homogeneous.

The two large divisions of Table II are (A) non-metallic luster and (B) metallic luster, but if the luster is in doubt it may be disregarded, in which case the sulfids of division 7 must be considered with division 8 and the remainder of division 7 with division 9. The minerals are arranged as far as possible according to the acid radical. This is the arrangement of minerals used in Part II (The Description of Important Minerals).

The Determination of Minerals by Optical Tests

The determination of minerals by optical tests is practically limited to those that are fairly transparent in thin slices or fragments, but many apparently opaque minerals become transparent or translucent when reduced to fragments. For many non-metallic minerals the optical determinations are easier to make and are more satisfactory than blowpipe and chemical tests. It should also be emphasized that some distinctions which are practically impossible by chemical methods may be made by means of the polarizing microscope. For example, the distinctions between orthoclase and microcline, and quartz and chalcedony. A convenient method for optical determination of minerals is to reduce the mineral to a coarse powder by pounding rather than grinding. The coarsest fragments that go through a 100-mesh sieve are examined in some liquid such as clove oil or cinnamon oil, and the shape, color, pleochroism, relief, interference colors, extinction angle, sign of elongation, etc. are noted. The indices of refraction with reference to a standard set of liquids are determined. A list of minerals arranged according to indices of refraction will be found on p. 207. The determination of the indices of refraction is often sufficient to completely determine a mineral but it is advisable to make confirmatory chemical tests. Some of these may be performed on a small scale

on a glass slip and the precipitates which are characteristic may be examined with the polarizing microscope.

SYNOPSIS OF TABLE I

A. The mineral appears in distinct euhedral crystals.

I. The crystal habit is equidimensional (isometric or pseudo-isometric).
II. The crystal habit is tabular.
III. The crystal habit is pyramidal.
IV. The crystal habit is prismatic.
V. The crystal habit is complex and not previously included.
VI. The crystals are obviously twins.

B. The mineral has well-defined structure.

I. The structure is columnar or bladed.
II. The structure is fibrous.
III. The structure is foliated or micaceous.
IV. The structure is colloform.
V. The structure is oölitic or pisolitic.

C. The mineral has good to perfect cleavage (or parting).

I. Cleavage in one direction.
II. Cleavage in two directions at right angles or nearly so.
III. Cleavage in two directions at oblique angles.
IV. Cleavage in three directions at right angles.
V. Cleavage in three directions; two at right angles, the third at an oblique angle.
VI. Cleavage in three directions at oblique angles.
VII. Cleavage in four or more directions.

D. The mineral in massive without prominent cleavage or any particular structure.

I. Luster, metallic or submetallic.
  1. Color—black to dark gray.
  2. Color—tin-white to light gray.
  3. Color—brass, bronze, red, brown, etc.
II. Luster, adamantine or subadamantine.
III. Luster, non-metallic (and not adamantine):
  1. Color—red or pink.
  2. Color—yellow.
  3. Color—green.

4. Color—blue.
5. White, colorless, or nearly so.
6. Color—gray.
7. Color—brown.
8. Black.

A. THE MINERAL APPEARS IN DISTINCT EUHEDRAL CRYSTALS.

I. THE CRYSTAL HABIT IS EQUIDIMENSIONAL (ISOMETRIC OR PSEUDO-ISOMETRIC).

1. Cubes or cube-like forms.

ANHYDRITE, p. 330. Pseudo-cubes.
Apophyllite, p. 406. Cleavage in one direction.
Argentite, p. 228. Metallic luster.
CALCITE, p. 291. Rhombohedral cleavage.
Cerargyrite, p. 253. Adamantine luster.
Chabazite, p. 410. Rhombohedrons of 85° angle.
Cuprite, p. 267. Adamantine luster.
Cryolite, p. 256. Pseudo-cubic.
FLUORITE, p. 254. Octahedral cleavage.
GALENA, p. 228. Metallic luster. Cubic cleavage.
HALITE, p. 251. Cubic cleavage.
Jarosite, p. 336. Pseudo-cubic rhombohedrons.
PYRITE, p. 236. Metallic luster. Crystals usually striated.
QUARTZ, p. 258. Rhombohedron of 86° angle.
Smaltite, p. 238. Metallic luster.
Sylvite, p. 253. Cubic cleavage; resembles halite.

2. Octahedrons or pseudo-octahedrons.

CHROMITE, p. 281. Metallic luster.
Cuprite, p. 267. Adamantine luster.
Diamond, p. 213. Adamantine luster.
FLUORITE, p. 254. Octahedral cleavage.
Franklinite, p. 280. Metallic luster.
GALENA, p. 228. Metallic luster. Cubic cleavage.
MAGNETITE, p. 279. Metallic luster.
PYRITE, p. 236. Metallic luster.
SPHALERITE, p. 231. Dododecahedral cleavage.
Spinel, p. 278. No cleavage.

3. Tetrahedrons or pseudo-tetrahedrons.
   CHALCOPYRITE, p. 244. Metallic luster.
   SPHALERITE, p. 231. Adamantine luster. Good cleavage
   TETRAHEDRITE, p. 247. Metallic luster.

4. Dodecahedrons.
   Cuprite, p. 267. Adamantine luster.
   Diamond, p. 213. Adamantine luster.
   GARNET, p. 371. Usually red or brown
   MAGNETITE, p. 279. Metallic luster

5. Trapezohedrons.
   Analcite, p. 410. Usually colorless.
   GARNET, p. 371. Usually red or brown
   Leucite, p. 355. Usually white.

6. Pyritohedrons.
   PYRITE, p. 236. Metallic luster.

II. THE CRYSTAL HABIT IS TABULAR.

1. Rhombic cross-section.
   Anglesite, p. 329. Adamantine luster.
   ARSENOPYRITE, p. 240. Metallic luster.
   BARITE, p. 327. Vitreous luster.
   Celestite, p. 328. Vitreous luster.
   GYPSUM, p. 332. Monoclinic.
   Marcasite, p. 239. Metallic luster.
   MUSCOVITE, p. 393. Perfect cleavage.

2. Square cross-section.
   Apophyllite, p. 406. Cleavage in one direction.
   Wulfenite, p. 340. Adamantine luster.

3. Rectangular cross-section.
   BARITE, p. 327. Good cleavage.

4. Hexagonal cross-section.
   APATITE, p. 313. Practically no cleavage.
   CALCITE, p. 291. Good cleavage.
   CHLORITE, p. 397. Perfect basal cleavage.
   CORUNDUM, p. 268. Triangular markings on base.
   Covellite, p. 234. Metallic luster.
   Dahllite, p. 315. Minute crystals.
   GRAPHITE, p. 216. Metallic luster.
   HEMATITE, p. 270. Metallic luster.

Ilmenite, p. 310. Metallic luster.
MICA GROUP, p. 392. Perfect cleavage in one direction.
Molybdenite, p. 227. Metallic luster.
Polybasite, p. 249. Metallic luster.
Stephanite, p. 248. Metallic luster.

III. THE CRYSTAL HABIT IS PYRAMIDAL.

1. Rhombic cross-section.

Anglesite, p. 329. Adamantine luster.
SULFUR, p. 217. Adamantine luster.

2. Square cross-section.

Apophyllite, p. 406. Cleavage in one direction.
CASSITERITE, p. 272. Adamantine luster.
Scheelite, p. 339. Sub-adamantine luster.
Vesuvianite, p. 378. Low pyramidal habit.
Zircon, p. 379. Adamantine luster.

3. Hexagonal cross-section.

CALCITE, p. 291. Rhombohedral cleavage.
CERUSSITE, p. 305. Adamantine luster.
CORUNDUM, p. 268. Steep hexagonal bipyramids.
DOLOMITE, p. 296. Resembles calcite.
HEMATITE, p. 270. Metallic luster.
Nitratine, p. 322. Resembles cleavage rhombohedron of calcite.
Pyrargyrite, p. 246. Metallic-adamantine luster.
QUARTZ, p. 258.
Rhodochrosite, p. 300. Resembles calcite.
SIDERITE p. 299. Resembles calcite.
Witherite, p. 305. Resembles quartz in form.

IV. THE CRYSTAL HABIT IS PRISMATIC.

1. Rhombic cross-section.

Adularia, p. 346. Cleavage oblique to prism.
Anglesite, p. 329. Adamantine luster.
Anthophyllite, p. 364. Resembles tremolite and hornblende.
BARITE, p. 327. Prismatic and basal cleavage.
HORNBLENDE, p. 365. Prism angle 56° and 124°.
Sillimanite, p. 383. One perfect cleavage.
Staurolite, p. 387. No cleavage.

Topaz, p. 380. Good cleavage normal to prism faces.
Tremolite, p. 364. Prism angle 56° and 124°.

2. Square cross-section.

Andalusite, p. 381. No cleavage.
Apophyllite, p. 406. Good cleavage in one direction.
Augite, p. 361.
Diopside, p. 360. Imperfect cleavage, often parting 1101.
Natrolite, p. 411. Prisms terminated by low pyramid.
ORTHOCLASE, p. 344. Monoclinic.
PYROXENE, p. 359. Monoclinic.
Rutile, p. 273. Metallic-adamantine luster.
Scapolite, p. 377. Prisms with low pyramids.
Topaz, p. 380. Good cleavage normal to prism faces.
Vesuvianite, p. 378. Prisms with low pyramids.
Zircon, p. 379. Prisms with low pyramids. Small crystals.

3. Hexagonal cross-section.

APATITE, p. 313. Practically no cleavage.
Aragonite, p. 302. Resembles calcite but cleavage imperfect.
Beryl, p. 368. No cleavage.
CALCITE, p. 291. Perfect rhombohedral cleavage.
CORUNDUM, p. 268. Triangular markings on base.
Dahllite, p. 315. Minute crystals.
EPIDOTE, p. 384. Good cleavage in one direction.
HORNBLENDE, p. 365. Prismatic cleavage.
Mimetite, p. 316. Adamantine luster.
Nepheline, p. 355. Crystals small.
Pyrargyrite, p. 246. Metallic-adamantine luster.
Pyromorphite, p. 315. Adamantine luster.
QUARTZ, p. 258. No cleavage.
TOURMALINE, p. 388. No cleavage. 3P intersect in A_3.
Tremolite, p. 364. Resembles hornblende in form.
Vanadinite, p. 317. Adamantine luster.
Willemite, p. 375. Hexagonal prism $11\bar{2}0$ and rhombohedron $10\bar{1}1$.

V. CRYSTAL HABIT COMPLEX AND NOT PREVIOUSLY INCLUDED.

Axinite, p. 391. Triclinic.
CALCITE, p. 291. Perfect rhombohedral cleavage.

Colemanite, p. 323. Perfect cleavage.
Datolite, p. 391. No cleavage; monoclinic.
Diopside, p. 360. Imperfect cleavage, often parting.
Microcline, p. 347. Apparently monoclinic; resembles orthoclase.
ORTHOCLASE, p. 344. Monoclinic.

VI. THE CRYSTALS ARE OBVIOUSLY TWINS.

1. Contact twins.

Albite, p. 350. Usually Carlsbad twin.
Aragonite, p. 302. Twin plane = {110}.
CALCITE, p. 291. See Figs. 458–461.
CASSITERITE, p. 272. Resembles rutile.
CERUSSITE, p. 305. Crystals at 60° angles.
Diamond, p. 213. Spinel twin like Fig. 438, p. 278.
EPIDOTE, p. 384. See Fig. 557.
GYPSUM, p. 332. Twin plane usually {100}.
HORNBLENDE, p. 365. Twin plane = {100}.
Microcline, p. 347. Resembles orthoclase.
ORTHOCLASE, p. 344. See Figs. 508 and 509.
PYROXENE, p. 359. Twin plane = {100}.
Rutile, p. 273. See Figs. 433–436.
Spinel, p. 278. Octahedrons twinned on {111}.

2. Penetration twins.

CALCITE, p. 291.
CERUSSITE, p. 305. Crystals at 60° angles.
FLUORITE, p. 254. Twin axis = cube diagonal.
Microcline, p. 347. Twin axis = *c*-axis.
ORTHOCLASE, p. 344. Twin axis = *c*-axis.
PYRITE, p. 236. See Fig. 257, p. 127.

3. Polysynthetic twinning striations.

CALCITE, p. 291. Striations parallel to long diagonal.
CORUNDUM, p. 268. Rhombohedral parting.
GALENA, p. 228. See Fig. 255 p. 127.
PLAGIOCLASE, p. 348. Striations usually on best cleavage.
Rutile, p. 273. See Fig. 434.
SPHALERITE, p. 231. Twin plane = {111}.

B. THE MINERAL HAS WELL-DEFINED STRUCTURE.

I. THE STRUCTURE IS COLUMNAR OR BLADED.

1. The mineral is scratched by the finger-nail.

	Sp. gr.	Remarks
STIBNITE, p. 225.....	4.5	Good cleavage in one direction.
Bismuthinite, p. 226.....	6.4	Resembles stibnite.

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

Colemanite, p. 323.....	2.4	Perfect cleavage in one direction.
CALCITE, p. 291.....	2.7	Perfect cleavage oblique to length.
Wollastonite, p. 369.....	2.8	Good cleavage.
Aragonite, p. 302.....	2.9	Imperfect cleavage parallel to length.
CALAMINE, p. 376.....	3.4	Subradiating crusts.
Kyanite, p. 382.....	3.6	Perfect cleavage.
Strontianite, p. 304.....	3.7	Resembles aragonite, except in spec. grav.
Goethite, p. 284.....	4.3	Yellow-brown streak.
Manganite, p. 285.....	4.3	Dark-brown streak. Metallic luster.
Enargite, p. 250.....	4.4	Grayish-black streak. Metallic luster.

3. The mineral is not scratched by a knife blade.

Beryl, p. 368.....	2.7	No cleavage.
Tremolite, p. 364.....	3.0	Cleavage in two directions at oblique angles.
TOURMALINE, p. 388...	3.1	No cleavage.
HORNBLENDE, p. 365..	3.2	Dark green or brown to black; perfect cleavage.
Clinozoisite, p. 386.....	3.3	Gray to pale green.
EPIDOTE, p. 384.....	3.4	Pistache green color.
Vesuvianite, p. 378.....	3.4	No distinct cleavage.
Kyanite, p. 382.....	3.6	Good cleavage in one direction.
Wolframite, p. 338.....	7.2	Good cleavage.

II. THE STRUCTURE IS FIBROUS.

1. The mineral is scratched by the finger-nail.

	Sp. gr.	Remarks
Ulexite, p. 324	1.6	Loosely compacted "cotton-balls."
Chrysotile, p. 400	2.2	Usually occurs in serpentine.
GYPSUM, p. 332	2.3	In sedimentary rocks.
Brucite, p. 288	2.4	May occur in serpentine.
Pyrophyllite, p. 401	2.8	Usually radiating. Pearly luster.
Pyrolusite, p. 274	4.8	Black. Metallic to dull

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

Stilbite, p. 409	2.1	Secondary mineral in cavities or seams.
Natrolite, p. 411	2.2	Secondary mineral in cavities or seams.
ANTIGORITE, p. 398	2.5	In serpentine.
CALCITE, p. 291	2.7	Perfect cleavage oblique to length.
TALC, p. 400	2.7	Soapy feel.
Wollastonite, p. 369	2.8	In limestone.
Aragonite, p. 302	2.9	Imperfect cleavage parallel to length.
Sillimanite, p. 383	3.2	In metamorphic rocks.
Strontianite, p. 304	3.7	Resembles aragonite.
Celestite, p. 328	3.9	Often pale blue.
MALACHITE, p. 307	3.9	Emerald green.
Goethite, p. 284	4.3	Yellow-brown streak.
Manganite, p. 285	4.3	Dark-brown streak.

3. The mineral is not scratched by a knife blade.

	Sp. gr.	Remarks
Tremolite, p. 364.....	3.0	Good cleavage; white pale green, or gray.
Anthophyllite, p. 364.....	3.1	Good cleavage. Usually brown.
Glaucophane, p. 367.....	3.1	Good cleavage. Blue black.
TOURMALINE, p. 388...	3.1	No cleavage. Usually black.
HORNBLENDE, p. 365..	3.2	Good cleavage. Dark green or brown to black.

III. THE STRUCTURE IS FOLIATED OR MICACEOUS.

1. The mineral is scratched by the finger-nail.

GRAPHITE, p. 216.....	2.1	Black. Metallic luster Gray streak.
GYPSUM, p. 332.....	2.3	Perfect cleavage.
Brucite, p. 288.....	2.4	Perfect cleavage.
TALC, p. 400.....	2.7	Soapy feel.
CHLORITE, p. 397.....	2.8	Light to dark green Flexible plates.
Molybdenite, p. 227.....	4.7	Green streak on glaze paper.

2. The mineral is not scratched by the finger-nail, but scratched by a knife blade.

Lepidolite, p. 395.....	2.8	Perfect cleavage. Lil colored.
MUSCOVITE, p. 393.....	2.8	Perfect cleavage. Lig colored.
Phlogopite, p. 397.....	2.8	Perfect cleavag Brown. In limestor
BIOTITE, p. 396.....	2.9	Perfect cleavag Black to deep brow
BARITE, p. 328.....	4.5	Very heavy.

3. The mineral is not scratched by a knife blade.

	Sp. gr.	Remarks
Albite, p. 350	2.6	Twinning lamellæ on ends of plates.
HEMATITE, p. 270	5.2	Metallic luster. Red streak.

IV. THE STRUCTURE IS COLLOFORM.

1. Mamillary, botryoidal, etc.

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

OPAL, p. 262	2.1	Usually clear and colorless.
Gibbsite, p. 286	2.4	Usually in bauxite.
CALCITE, p. 291	2.7	In limestone.
Dahllite, p. 315	3.0	In phosphorite.
LIMONITE, 286	3.8	Yellow-brown streak. Amorphous.
MALACHITE, p. 307	3.9	Emerald green.
Goethite, p. 284	4.3	Yellow-brown streak. Crystalline.
SMITHSONITE, p. 301	4.4	Curved cleavage.

3. The mineral is not scratched by a knife blade.

OPAL, p. 262	2.1	Usually clear and colorless.
CHALCEDONY, p. 261	2.6	Waxy to dull. Translucent.
PSILOMELANE, p. 289	4.2	Black. Dull luster.
Turyite, p. 271	4.5	Red streak. Amorphous.
HEMATITE, p. 270	5.2	Red streak. Crystalline.
CASSITERITE, p. 272	7.0	Colorless streak. Adamantine luster.

V. THE MINERAL HAS AN OÖLITIC OR PISOLITIC STRUCTURE.

1. The mineral is scratched by the finger-nail.

	Sq. gr.	Remarks
Glauconite, p. 406.....	2.3	Green. In sandstone
CLIACHITE, p. 287.....	2.5	Pale colors to red. I bauxite.

2. The mineral is not scratched by the finger-nail, but i scratched by a knife blade.

CLIACHITE, p. 287.....	2.5	Pale colors to red. I bauxite.
CALCITE, p. 291.....	2.7	White to gray. I limestones.
COLLOPHANE, p. 319..	2.8	Any color. In phos phorites.
SIDERITE, p. 286.....	3.8	Brown with pale strea
LIMONITE, p. 286.....	3.8	Yellow-brown streak.
HEMATITE, p. 270	5.2	Red streak.

3. The mineral is not scratched by a knife blade.

CHALCEDONY, p. 261...	2.6	Light gray. Quar usually present.

C. THE MINERAL DOES NOT APPEAR IN DISTINCT CRYSTALS AND HAS NO PARTICULAR STRUCTURE, BUT DOES HAVE GOOD TO PERFECT CLEAVAGE (OR PARTING.)

I. CLEAVAGE (OR PARTING) IN ONE DIRECTION.

1. The mineral is scratched by the finger-nail.

GRAPHITE, p. 216.....	2.1	Black. Metallic lust
GYPSUM, p. 332.....	2.3	Two other less perf cleavages.
Brucite, p. 288.....	2.4	No secondary clea ages.
Vivianite, p. 318.....	2.6	Blue.
TALC, p. 400.....	2.7	Soapy feel.
CHLORITE, p. 397.....	2.8	Light to dark green. Plates are flexible.
STIBNITE, p. 225.....	4.5	Cleavage parallel length.
Molybdenite, p. 227.....	4.7	Greenish streak glazed paper.
Bismuthinite, p. 226.....	6.4	Resembles stibnite.

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

Heulandite, p. 408.....	2.2	Pearly luster on cleavage face. Monoclinic.
Apophyllite, p. 406.....	2.3	Pearly luster on cleavage face. Tetragonal.
Colemanite, p. 323.....	2.4	Vitreous luster.
Lepidolite, p. 395.....	2.8	Lilac colored.
MUSCOVITE, p. 393.....	2.8	Light colored.
Sericite, p. 304.....	2.8	Scaly. Fine-grained.
Phlogopite, p. 397.....	2.8	Brown. In limestones.
BIOTITE, p. 396.....	2.8	Black to dark brown.
Kyanite, p. 382.....	3.6	Bladed structure.
Celestite, p. 328.....	3.9	Resembles barite.
Goethite, p. 284.....	4.3	Cleavage parallel to length. Yellow-brown streak.
Wolframite, p. 338.....	7.4	Black submetallic luster.

3. The mineral is not scratched by a knife blade.

Spodumene, p. 370.....	3.1	Also prismatic cleavages.
Diopside, p. 360.....	3.2	Basal parting. Imperfect prismatic cleavage.
EPIDOTE, p. 384.....	3.4	Pistache green.
Topaz, p. 380.....	3.5	Cleavage perpendicular to prism faces.
Kyanite, p. 382.....	3.6	Bladed structure.
CORUNDUM, p. 268.....	4.0	Basal parting with triangular striations.
Goethite, p. 284.....	4.3	Yellow-brown streak.
Wolframite, p. 338.....	7.4	Black. Submetallic luster.

II. CLEAVAGE (OR PARTING) IN TWO DIRECTIONS A RIGHT ANGLES OR NEARLY SO.

1.

2.

3. The mineral is not scratched by a knife blade.

	Sp. gr.	Remarks
Adularia, p. 346	2.6	Usually clear and colo less. Rhombic habi
ORTHOCLASE, p. 344	2.6	No twinning striation
Microcline, p. 347	2.6	Resembles orthoclas May show cross hatching.
PLAGIOCLASE, p. 348	2.6	Usually shows twinnin striations.
Scapolite, p. 377	2.7	Imperfect cleavage.
Wollastonite, p. 369	2.8	Usually in limestones.
Spodumene, p. 370	3.1	Often shows pinacoid parting.
Diopside, p. 360	3.2	White to green.
Augite, p. 361	3.3	Dark green to black.
Rhodonite, p. 362	3.6	Usually red. Non-m tallic.
Rutile, p. 273	4.2	Dark red; metallic-ad mantine luster.

III. CLEAVAGE (OR PARTING) IN TWO DIRECTIONS A OBLIQUE ANGLES.

1.

2. The mineral is not scratched by the finger-nail, but scratched by a knife blade.

Enargite, p. 250	4.4	Columnar structure.

3. The mineral is not scratched by a knife blade.

Tremolite, p. 364	3.0	White, gray, pale gree
Anthophyllite, p. 364	3.1	Usually brown.
HORNBLENDE, p. 365	3.2	Dark green or brown black.
Titanite, p. 412	3.5	Yellow to brown.

IV. CLEAVAGE (OR PARTING) IN THREE DIRECTIONS AT RIGHT ANGLES.

1. The mineral is scratched by the finger-nail.

	Sp. gr.	Remarks
Sylvite, p. 253.....	2.0	Bitter taste.

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

HALITE, p. 251.....	2.1	Soluble in water (taste).
ANHYDRITE, p. 330.....	2.9	Pseudo-cubic cleavage.
Cryolite, p. 256.....	3.0	Almost disappears in water.
GALENA, p. 228.....	7.5	Lead gray. Metallic luster.

3. The mineral is not scratched by a knife blade.

CORUNDUM, p. 268.....	4.0	Very hard. Pseudo-cubic parting.

V. CLEAVAGE IN THREE DIRECTIONS; TWO AT RIGHT ANGLES, THE THIRD AT AN OBLIQUE ANGLE.

1. The mineral is scratched by the finger-nail.

GYPSUM, p. 332.....	2.3	Pearly luster.

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

Celestite, p. 328.....	3.9	Prismatic cleavage imperfect.
BARITE, p. 327.....	4.5	Prismatic cleavage perfect.

3. The mineral is not scratched by a knife blade.

Spodumene, p. 370.....	3.1	Pinacoidal parting.

VI. CLEAVAGE IN THREE DIRECTIONS AT OBLIQUE ANGLES (RHOMBOHEDRAL CLEAVAGE).

1.

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

	Sp. gr.	Remarks
CALCITE, p. 291.....	2.7	Any color.
DOLOMITE, p. 296.....	2.8	Resembles calcite, but cleavage often curved.
Magnesite, p. 298.....	3.1	Color varies. Chemical tests necessary.
Rhodochrosite, p. 300....	3.5	Pink to red.
SIDERITE, p. 299.....	3.8	Brown.

3.

VII. CLEAVAGE (OR PARTING) IN FOUR OR MORE DIRECTIONS.

1.

2. The mineral is not scratched by the finger-nail, but is scratched by a knife blade.

CALCITE, p. 291.....	2.7	Rhombohedral cleavage plus parting.
FLUORITE, p. 254.....	3.2	Octahedral cleavage.
SPHALERITE, p. 231....	4.0	Dodecahedral cleavage Adamantine luster.

3. The mineral is not scratched by a knife blade.

Scapolite, p. 377.....	2.7	Prismatic cleavage.
Diamond, p. 213.....	3.5	Adamantine luster.
CORUNDUM, p. 268.....	4.0	Rhombohedral and basal parting.
MAGNETITE, p. 279....	5.1	Octahedral parting Metallic luster.

D. THE MINERAL IS MASSIVE WITHOUT PROMINENT CLEAVAGE OR ANY PARTICULAR STRUCTURE.

I. LUSTER METALLIC OR SUBMETALLIC. (The thin edges are opaque.)

1. Color black to dark gray.

		Sp. gr.	Remarks
(*a*) The mineral is scratched by the finger-nail.	**GRAPHITE**, p. 216...	2.1	Streak gray on glazed paper.
	STIBNITE, p. 215.....	4.5	Lead-gray streak.
	Molybdenite, p. 227...	4.7	Greenish streak on glazed paper.
	Pyrolusite, p. 274.....	4.8	Streak black.
	Argentite, p. 228	7.3	Very sectile.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**TETRAHEDRITE**, p. 247.....	4.7	Very brittle.
	CHALCOCITE, p. 230.	5.7	Subsectile.
	Pyrargyrite, p. 246....	5.8	Red on thin edges.
	Stephanite, p. 248.....	6.2	Black on thin edges.
	Wolframite, p. 338.....	7.4	Submetallic luster.
(*c*) The mineral is not scratched by a knife blade.	**PSILOMELANE**, p. 273.	4.2	No cleavage or structure.
	Rutile, p. 273.....	4.2	Reddish brown.
	CHROMITE, p. 281...	4.4	Brown streak. Occurs in serpentine.
	Ilmenite, p. 310.....	4.7	Resembles hematite.
	Hausmannite, p. 282...	4.8	Chestnut-brown streak.
	MAGNETITE, p. 279.	5.1	Strongly magnetic.
	Franklinite, p. 280.....	5.1	Associated with willemite and zincite.
	HEMATITE, p. 270...	5.2	Red-brown streak.
	Columbite, p. 312.....	5.6	Submetallic luster.
	Wolframite, p. 338.....	7.4	Submetallic luster.
	CASSITERITE, p. 272	7.5	Adamantine luster.
	Pitchblende, p. 324....	7.5	Pitchy luster.

2. Color tin-white to light gray.

		Sp. gr.	Remarks
(*a*) The mineral is scratched by the finger-nail.	**STIBNITE**, p. 225.....	4.5	Lead-gray streak.
	Molybdenite, p. 227...	4.7	Greenish streak glazed paper.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**Iron**, p. 223.....	7.0	Strongly magnetic
	GALENA, p. 228.....	7.5	Granular structu due to cleavage.
	SILVER, p. 220.....	10.5	Usually tarnished.
	Platinum, p. 222.....	15.0– 19.0	In grains, scales, a nuggets.
(*c*) The mineral is not scratched by a knife blade.	**ARSENOPYRITE**, p. 240.	6.0	Usually occurs w pyrite, galena, et
	Smaltite, p. 238.....	6.2	Usually occurs w silver minerals.

3. Color brass, bronze, red, brown, etc.

(*a*) The mineral is scratched by the finger-nail.			
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**CHALCOPYRITE**, p. 244.....	4.2	Brass yellow.
	PYRRHOTITE, p. 235.	4.6	Somewhat magne
	Pentlandite, p. 233....	4.8	Non-magnetic.
	BORNITE, p. 245.....	5.1	Peculiar purp brown. Easily t nished.
	Cuprite, p. 267.....	6.0	Deep red transluce
	COPPER, p. 221.....	8.8	Characteristic colo
	Calaverite, p. 242.....	8.8	Brittle.
	GOLD, p. 218.....	15.0– 19 0	Malleable.
(*c*) The mineral is not scratched by a knife blade.	**Rutile**, p. 273.....	4.2	Brownish red.
	Marcasite, p. 239.....	4.9	Resembles pyrite.
	PYRITE, p. 236.....	5.0	Brass yellow.

II. LUSTER ADAMANTINE TO SUB-ADAMANTINE.

(Brilliant, but transparent or translucent on thin edges.)

		Sp. gr.	Remarks
a) The mineral is scratched by the finger-nail.	**SULFUR**, p. 217.....	2.0	Brittle.
	Cerargyrite, p. 253....	5.5	Very sectile.
b) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**SPHALERITE**, p. 231.	4.0	Usually shows good cleavage.
	Pyrargyrite, p. 246....	5.8	Red on thin edges.
	Cuprite, p. 267.....	6.0	Deep red translucent.
	Scheelite, p. 339.....	6.0	Sub-adamantine luster.
	Anglesite, p. 329.....	6.3	Resembles cerussite.
	CERUSSITE, p. 305...	6.5	Colorless, white or pale colors.
	Wulfenite, p. 340.....	6.7	Usually yellow to red.
	Pyromorphite, p. 315..	6.8	Usually green or brown.
	Vanadinite, p. 317....	6.8	Usually red.
	Mimetite, p. 316.....	7.2	Resembles vanadinite.
	CINNABAR, p. 234....	8.0	Vermilion-red.
c) The mineral is not scratched by a knife blade.	Diamond, p. 213.....	3.5	Loose crystals. Octahedral cleavage.
	Spinel, p. 278.....	3.6	Usually in octahedral crystals or grains.
	CORUNDUM, p. 268..	4.0	More or less perfect hexagonal crystals.
	Rutile, p. 273.....	4.2	Reddish brown.
	Zircon, p. 379.....	4.6	Usually brown.
	CASSITERITE, p. 272	7.5	Very heavy.

III. LUSTER NON-METALLIC (AND NOT ADAMANTINE).

1. Color red or pink.

(*a*) The mineral is scratched by the finger-nail.	**GYPSUM**, p. 332.....	2.3	Crystalline granul
	CLIACHITE, p. 287...	2.5	Usually pisoliti Clay-like.
	HEMATITE, p. 270...	5.2	Earthy structure.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	Chabazite, p. 262.....	2.1	Cube-like rhomboh drons.
	OPAL, p. 262.....	2.1	Luster—greasy.
	Alunite, p. 335.....	2.6	Difficult to recogni at sight.
	CALCITE, p. 291.....	2.7	Usually shows clea age.
	DOLOMITE, p. 296...	2.8	Resembles calcite.
	Lepidolite, p. 395.....	2.8	Lilac-colored scales
	ANHYDRITE, p. 330..	2.9	Resembles limestor
	Magnesite, p. 298.....	3.1	Rhombohedral clea age.
	Rhodochrosite, p. 300.	3.5	Usually shows rho bohedral cleavage
	BARITE, p. 327.....	4.5	Very heavy.
(*c*) The mineral is not scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Luster greasy.
	CHALCEDONY, p. 261	2.6	Luster dull.
	QUARTZ, p. 258.....	2.6	Luster vitreous.
	Beryl, p. 368.....	2.7	Resembles quartz.
	Andalusite, p. 381.....	3.1	Usually has colu nar structure.
	Chondrodite, p. 402....	3.1	Usually in crystall limestone.
	TOURMALINE, p. 388	3.1	Usually in prisma crystals.
	Rhodonite, p. 362.....	3.6	Resembles rhod chrosite.
	GARNET, p. 371.....	3.8–4.2	May show granu structure.
	Willemite, p. 375.....	4.1	Usually with fra linite.

2. Color yellow.

		Sp. gr.	Remarks
(*a*) The mineral is scratched by the finger-nail.	**GYPSUM**, p. 332.....	2.3	Crystalline granular.
	Carnotite, p. 321.....	4.1	In sandstone.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	ANTIGORITE, p. 398.	2.5	Compact; dull luster.
	CALCITE, p. 291.....	2.7	Usually shows cleavage.
	COLLOPHANE, p. 319	2.8	Amorphous, no cleav.
	Jarosite, p. 336.....	3.2	Earthy.
	LIMONITE, p. 286....	3.8	Yellow-brown streak.
	SMITHSONITE, p. 301.....	4.4	Curved cleavage.
	Stibiconite, p. 275.....	5.2	Pale yellow.
(*c*) The mineral is not scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	CHALCEDONY, p. 261	2.6	Dull luster.
	QUARTZ, p. 258.....	2.6	Vitreous luster.
	Beryl, p. 368.....	2.7	Resembles quartz.
	GARNET, p. 371.....	3.8	No cleavage or structure.
	Willemite, p. 375.....	4.1	Usually with franklinite.

3. Color green.

(*a*) The mineral is scratched by the finger-nail.	**Glauconite**, p. 406.....	2.3	Usually in grains.
	Garnierite, p. 404.....	2.5	Massive apple-green.
	TALC, p. 400.....	2.7	Pale green.
	CHLORITE, p. 397...	2.8	Scaly. Light to dark green.
	Cerargyrite, p. 253.....	5.5	Very sectile.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	CHRYSOCOLLA, p. 405.....	2.1	Bluish-green.
	ANTIGORITE, p. 398	2.5	Usually compact.
	APATITE, p. 313.....	3.2	No cleavage.
	Brochantite, p. 332....	3.9	Resembles malachite.
	MALACHITE, p. 307..	3.9	Usually fibrous.
	SMITHSONITE, p. 301.....	4.4	Curved rhombohedral cleavage.
	Pyromorphite, p. 315..	6.8	Occurs with lead minerals.

		Sp. gr.	Remarks
(*c*) The mineral is not scratched by a knife blade.	**OPAL**, p. 262	2.1	Greasy luster.
	CHALCEDONY, p. 261	2.6	Dull luster.
	Beryl, p. 368	2.7	Prismatic crystals.
	Turquois, p. 320	2.7	Bluish green. Appently amorphous.
	Prehnite, p. 387	2.9	With zeolites.
	TOURMALINE, p. 388	3.1	Prismatic crystals.
	Diopside, p. 360	3.2	In limestones.
	Forsterite, p. 374	3.2	Granular.
	OLIVINE, p. 373	3.3	Granular.
	Clinozoisite, p. 386	3.3	Pale green.
	EPIDOTE, p. 384	3.4	Pistache green.
	Vesuvianite, p. 378	3.4	
	GARNET, p. 371	3.8–4.2	May be granular.
	Willemite, p. 375	4.1	With franklinite.
4. Color blue.			
(*a*) The mineral is scratched by the finger-nail.	**Chalcanthite**, p. 334	2.2	Soluble in wat (taste).
	Vivianite, p. 318	2.6	Cleavable or earth
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**CHRYSOCOLLA**, p. 405	2.1	Greenish blue.
	Lazurite, p. 357	2.4	Dark blue. With rite. (lapis lazu
	Lepidolite, p. 395	2.8	Scaly. With tourn line.
	CALCITE, p. 291	2.7	Shows cleavage.
	ANHYDRITE, p. 330	2.9	Resembles limesto
	Azurite, p. 307	3.8	Deep blue.
	Celestite, p. 328	3.9	Resembles barite.
(*c*) The mineral is not scratched by a knife blade.	**Sodalite**, p. 356	2.3	With feldspars.
	CHALCEDONY, p. 261	2.6	Compact, apparen amorphous.
	Beryl, p. 368	2.7	Prismatic crystals
	Turquois, p. 320	2.7	Greenish blue.
	Glaucophane, p. 367	3.1	Dark blue to bl black.
	TOURMALINE, p. 388	3.1	Prismatic crystals
	CORUNDUM, p. 268	4.0	Usually bluish-gr Very hard.

5. White, colorless, or nearly so (pale tints of any hue are included here).

		Sp. gr.	Remarks
(*a*) The mineral is scratched by the finger-nail.	Carnallite, p. 257	1.6	Soluble in water.
	Ulexite, p. 324	1.6	Shows minute fibres.
	Sylvite, p. 253	2.0	Soluble in water.
	Hydromagnesite, p. 308	2.1	Usually in serpentine.
	Halloysite, p. 404	2.2	Clay-like.
	GYPSUM, p. 332	2.3	Often granular.
	Nitratine, p. 322	2.3	Soluble in water.
	Brucite, p. 288	2.4	Difficult to recognize.
	CLIACHITE, p. 287	2.5	Usually pisolitic. Clay-like.
	Kaolinite, p. 403	2.6	Clay-like.
	TALC, p. 400	2.7	Soapy feel.
	Sericite, p. 394	2.8	Scaly, in part like talc.
	Pyrophyllite, p. 401	2.8	Resembles talc.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	HALITE, p. 251	2.1	Soluble in water.
	Kainite, p. 331	2.1	Soluble in water.
	ZEOLITE, p. 407	2.1–2.3	Crystalline. Variable.
	OPAL, p. 262	2.1	Amorphous.
	Hydromagnesite, p. 308	2.1	Usually in serpentine.
	Colemanite, p. 323	2.4	Difficult to recognize.
	Gibbsite, p. 286	2.4	Usually in bauxite.
	CALCITE, p. 291	2.7	Usually good cleavage.
	DOLOMITE, p. 296	2.8	Resembles calcite.
	COLLOPHANE, p. 319	2.8	Difficult to recognize.
	Wollastonite, p. 369	2.8	Columnar or fibrous.
	ANHYDRITE, p. 330	2.9	Resembles limestone.
	Aragonite, p. 302	2.9	Cleavage imperfect or lacking.
	Cryolite, p. 256	3.0	Almost disappears in water.
	Dahllite, p. 315	3.0	Usually an incrustation.
	Magnesite, p. 298	3.1	Resembles porcelain.
	FLUORITE, p. 254	3.2	Shows cleavage.

		Sp. gr.	Remarks
	CALAMINE, p. 376...	3.4	Subradiating structure.
	Strontianite, p. 304....	3.7	Resembles aragonite
	Celestite, p. 328.....	3.9	Resembles barite.
	Witherite, p. 305.....	4.3	Very heavy.
	SMITHSONITE, p. 301	4.4	Curved cleavage.
	BARITE, p. 327.....	4.5	Usually shows platy structure.
	Stibiconite, p. 275.....	5.2	Yellowish white.
	Scheelite, p. 339.....	6.0	Subadamantine luster.
(*c*) The mineral is not scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster. Hyalite, vitreous.
	CHALCEDONY, p. 261	2.6	Dull luster.
	QUARTZ, p. 258.....	2.6	Vitreous luster.
	Adularia, p. 346.....	2.6	Vein mineral.
	Microcline, p. 347.....	2.6	Like orthoclase.
	ORTHOCLASE, p. 344	2.6	No twin striations.
	PLAGIOCLASE, p. 348	2.6	Usually with twin striations.
	Nepheline, p. 355.....	2.6	Greasy luster.
	Beryl, p. 368.....	2.7	Resembles quartz.
	Scapolite, p. 377.....	2.7	More or less columnar.
	Datolite, p. 391.....	2.9	Colorless to greenish white.
	Spodumene, p. 370....	3.1	Shows more or less cleavage.
	Diopside, p. 360.....	3.2	White to pale green
	Forsterite, p. 374.....	3.2	Difficult to recognize
	GARNET, p. 371.....	3.8–4.2	Often granular.

6. Color gray.

		Sp. gr.	Remarks
(*a*) The mineral is scratched by the finger-nail.	**GYPSUM**, p. 332.....	2.3	Usually granular.
	Cerargyrite, p. 253.....	5.5	Very sectile.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Amorphous.
	Gibbsite, p. 286.....	2.4	Occurs in bauxite.
	CALCITE, p. 291.....	2.7	Usually shows cleavage.
	DOLOMITE, p. 296...	2.8	Resembles calcite.
	COLLOPHANE, p. 319	2.8	Amorphous. No cleavage.
	ANHYDRITE, p. 330..	2.9	Resembles calcite.
	Magnesite, p. 298.....	3.1	Resembles calcite.
	SIDERITE, p. 299....	3.8	Too heavy for calcite.
	SMITHSONITE, p. 301.	4.4	Usually shows curved cleavage.
	BARITE, p. 327.....	4.5	Usually more or less platy.
	Anglesite, p. 329.....	6.3	Very heavy. Associated with lead minerals.
(*c*) The mineral is not scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	CHALCEDONY, p. 261	2.6	Dull luster. Compact.
	QUARTZ, p. 258.....	2.6	Vitreous luster.
	ORTHOCLASE, p. 344	2.6	Usually shows cleavage.
	PLAGIOCLASE, p. 348	2.6	Usually shows cleavage and twin striations.
	Nepheline, p. 355.....	2.6	Greasy luster.
	Scapolite, p. 377.....	2.7	More or less columnar.
	Andalusite, 381.....	3.1	Associated with mica.
	Spodumene, p. 370....	3.1	Shows cleavage.
	Forsterite, p. 374.....	3.2	Granular.
	Clinozoisite, p. 386....	3.3	Yellowish or greenish gray.
	CORUNDUM, p. 268.	4.0	Shows parting.

7. Color brown.

		Sp. gr.	Remarks
(*a*) The mineral is scratched by the finger-nail.	**GYPSUM**, p. 332.....	2.3	Crystalline.
	CLIACHITE, p. 287...	2.5	Usually pisolitic. Amorphous.
	LIMONITE, p. 286....	3.8	Amorphous. Yellow-brown streak.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	ANTIGORITE, p. 398.	2.5	Compact.
	CALCITE, p. 291	2.7	Too light for siderite.
	COLLOPHANE, p. 319	2.8	Difficult to recognize.
	APATITE, p. 313.....	3.2	Reddish brown.
	Jarosite, p. 336.....	3.2	Yellow to brown.
	LIMONITE, p. 286....	3.8	Amorphous. Yellow-brown streak.
	SIDERITE, p. 299.....	3.8	Rhombohedral cleavage like calcite.
	SPHALERITE, p. 231.	4.0	Usually shows cleavage.
	PSILOMELANE, p. 289.....	4.2	Earthy and dull.
	Goethite, p. 284.....	4.3	Yellow-brown streak.
(*c*) The mineral is not scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	CHALCEDONY, p. 261	2.6	Dull luster.
	TOURMALINE, p. 388	3.1	In crystalline limestone.
	Vesuvianite, p. 378....	3.4	Usually columnar.
	Titanite, p. 412	3.5	Adamantine luster.
	Staurolite, p. 387.....	3.7	Prismatic crystals.
	GARNET, p. 371.....	3.8–4.2	No cleavage. May be granular.
	Rutile, p. 273.....	4.2	Reddish brown.
	CASSITERITE, p. 272.	7.5	Very heavy.

8. Black. (Very dark shades of any color are included here.)

		Sp. gr.	Remarks
(*a*) The mineral is scratched by the finger-nail.	**GRAPHITE**, p. 216....	2.1	Earthy and dull.
	PSILOMELANE, p. 289.....	4.2	Dull luster.
	Pyrolusite, p. 274.....	4.8	Usually more or less fibrous.
(*b*) The mineral is not scratched by the finger-nail, but is scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	ANTIGORITE, p. 398.	2.5	Usually greenish-black.
	CALCITE, p. 291.....	2.7	Usually shows cleavage.
	COLLOPHANE, p. 319	2.8	Often oölitic.
	SPHALERITE, p. 231.	4.0	Good cleavage.
	PSILOMELANE, p. 289.....	4.2	Dull luster.
(*c*) The mineral is not scratched by a knife blade.	**OPAL**, p. 262.....	2.1	Greasy luster.
	CHALCEDONY, p. 261	2.6	Dull luster
	QUARTZ, p. 258.....	2.6	Vitreous luster.
	TOURMALINE, p. 388	3.1	No cleavage.
	PYROXENE, p. 359...	3.2	Imperfect cleavage.
	Hypersthene, p. 359...	3.4	Lamellar structure.
	Spinel, p. 278	3.6	Usually in octahedral crystals.
	LIMONITE, p. 286....	3.8	Yellow-brown streak.
	GARNET, p. 371.....	3.8–	Usually in crystals.
	PSILOMELANE, p. 289.....	4.2 4.2	Dull luster.
	Rutile, p. 273.....	4.2	Difficult to recognize.
	CASSITERITE, p. 272.	7.5	Very heavy.

SYNOPSIS OF TABLE II

A. MINERALS WITH NON-METALLIC LUSTER.

(If the luster is in doubt it may be disregarded, in which case the sulfids of division 7 should be included with division 8 and the remainder of division 7 with those of division 9.)

1. Carbonates (the mineral effervesces in HCl).
2. Sulfates (the water solution of the Na_2CO_3 fusion gives a white ppt. with $BaCl_2$).
3. Silicates (fragments are insoluble in a $NaPO_3$ bead).
4. Phosphates and Arsenates (the HNO_3 solution of the Na_2CO_3 fusion gives a yellow ppt. with $(NH_4)_2MoO_4$).
5. Chromates, Vanadates, and Molybdates (green $NaPO_3$ bead in R.F.).
6. Chlorids ($NaPO_3$ bead with CuO gives blue flame).
7. Not previously included.

B. MINERALS WITH METALLIC OR SUB-METALLIC LUSTER.

8. Sulfids and Sulfo-salts (the Na_2CO_3 fusion made on mica O.F. stains a moistened silver coin).
9. Not previously included.

A. MINERALS WITH NON-METALLIC LUSTER

Division 1.—Carbonates (Including Carbonate-phosphates)

The mineral effervesces in HCl (either in the cold or upon heating) with the production of a colorless, odorless gas (CO_2).

(It should be noted that calcite is a common impurity in many other minerals.)

Closed tube		Fusibility	Tests	Mineral	Composition	Page
(a) The mineral turns dark on heating in the closed tube.	H_2O in closed tube.	Easily fusible	Cu test: green	**MALACHITE**	$Cu_2(OH)_2CO_3$	307
			Cu test: blue	**Azurite**	$Cu_3(OH)_2(CO_3)_2$	307
		Fusible with difficulty.	PO_4 test	**COLLOPHANE**	$3Ca_3(PO_4)_2 \cdot Ca(CO_3,F_2)(H_2O)_x$	319
	No H_2O in closed tube.		Abundant Fe	**SIDERITE**	$FeCO_3$	299
		Infusible	Small amount Fe	**DOLOMITE**	$Ca(Mg, Fe)(CO_3)_2$	296
			Mn bead test	**Rhodochrosite**	$MnCO_3$	300
(b) The mineral turns yellow on heating in the closed tube.	No H_2O in closed tube.	Easily fusible.	Pb on coal	**CERUSSITE**	$PbCO_3$	305
		Infusible	$Co(NO_3)_2$ test	**SMITHSONITE**	$ZnCO_3$	301
(c) The mineral does not change color appreciably on heating in the closed tube.	No H_2O in closed tube.	Easily fusible.	Green flame	**Witherite**	$BaCO_3$	305
		Infusible	Crimson flame	**Strontianite**	$SrCO_3$	304
			Ca test	**CALCITE**	$CaCO_3$	291
				Aragonite	$CaCO_3$	302
			Mg test	**DOLOMITE**	$CaMg(CO_3)_2$	296
				Magnesite	$MgCO_3$	298
				Hydromagnesite	$Mg_4(OH_2)(CO_3)_3 \cdot 3H_2O$	308
	H_2O in the closed tube.	Fusible with difficulty.	PO_4 test	**Dahllite**	$3Ca_3(PO_4)_2 \cdot CaCO_3$	315

Division 2.—Sulfates

A water solution of the Na_2CO_3 fusion gives a white ppt. with a $BaCl_2$ solution, which is insoluble in HCl. (It is necessary to add HCl for the excess of Na_2CO_3 always gives a ppt. of $BaCO_3$, but this is insoluble in HCl.) An acid solution of the residue may be tested for the metal.

Solubility	Fusibility	Tests	Mineral	Composition	Page
(*a*) The mineral is soluble in water (decided taste).	2	Wet test for Mg.	**Kainite**	$MgSO_4 \cdot KCl \cdot 3H_2O$	331
	3	Gives copper on iron.	**Chalcanthite**	$CuSO_4 \cdot 5H_2O$	334
(*b*) The mineral is insoluble in water, but is easily soluble in HCl.	3½	No ppt. with NH_4OH.	**GYPSUM**	$CaSO_4 \cdot 2H_2O$	332
	3½	Blue color with NH_4OH.	**Brochantite**	$Cu_4(OH)_6SO_4$	332
	4½	Brown ppt. with NH_4OH.	**Jarosite**	$KFe_3(OH)_6(SO_4)_2$	336
(*c*) The mineral is soluble with difficulty in HCl.	3½	Micro-gypsum forms.	**ANHYDRITE**	$CaSO_4$	330
	2½	Adamantine $PbCl_2$ forms.	**Anglesite**	$PbSO_4$	329
	4	See p. 42 for Ba test.	**BARITE**	$BaSO_4$	327
(*d*) The mineral is insoluble in HCl.	4	See p. 51 for Sr test.	**Celestite**	$SrSO_4$	328
	Infusible	Blue with $Co(NO_3)_2$.	**Alunite**	$KAl_3(OH)_6(SO_4)_2$	335

Fragments are insoluble in a hot $NaPO_3$ bead. The presence of silica may be confirmed by dissolving a Na_2CO_3 fusion of the powdered mineral in dilute HNO_3. On evaporating the solution, gelatinous silica separates and is carefully dehydrated. After filtering off the silica, the filtrate may be tested for the various metals.

The finely powdered mineral is heated in dilute HCl for several minutes. The solution is filtered off and evaporated on a watch-glass.

Solubility	Fusibility	Tests		Mineral	Composition	Page
(*a*) Gelatinizes with HCl.	2	Green flame B.		**Datolite**	$CaB(OH)SiO_4$	391
	2½	Water given off c.t. low temp.	Na flame	**Natrolite**	$Na_2Al_2Si_3O_{10}\cdot 2H_2O$	411
	4	H_2S odor with HCl.	Na flame	**Lazurite**	$Na_8Al_3S(SiO_4)_3$	357
	4	Cl test $NaPO_3$ bead.	Na flame	**Sodalite**	$Na_4Al_3Cl(SiO_4)_3$	356
	4	No Cl or S		**Nepheline**	$(Na,K)AlSiO_4$	355
	5	No H_2O in c.t.		**Willemite**	$(Zn,Mn)_2SiO_4$	375
	6	H_2O in c.t.		**CALAMINE**	$Zn(OH)_2SiO_3$	376
	Infusible	No H_2O in c.t.		**OLIVINE**	$(Mg,Fe)_2SiO_4$	373
	Infusible	No H_2O in c.t.		**Forsterite**	Mg_2SiO_4	374
	Infusible	A little H_2O at high temp.		**Chondrodite**	$Mg_5(F,OH)(SiO_4)_2$	402
	Infusible	No H_2O in c.t.		**Willemite**	Zn_2SiO_4	375
(*b*) Decomposed by HCl with the separation of slimy silica. A residue is left on evaporation of the filtered liquid.	2	Contains no Al.		**Apophyllite**	$(H,K)_2Ca(SiO_3)_2\cdot H_2O$	406
	2	Small amount H_2O.		**Prehnite**	$H_2Ca_2Al_2(SiO_4)_3$	387
	3	Must be distinguished by xl. form or opt. tests.	Zeolites	**Chabazite**	$(Ca,Na_2)Al_2(SiO_3)_4\cdot 6H_2O$	410
	3		Zeolites	**Stilbite**	$H_4(Ca,Na_2)Al_2(SiO_3)_6\cdot 4H_2O$	409
	3		Zeolites	**Heulandite**	$H_4CaAl_2(SiO_3)_6\cdot 3H_2O$	408
	3	No Ca test.	Zeolites	**Analcite**	$NaAl(SiO_3)_2\cdot H_2O$	410
	3			**Scapolite**	Ca, Na, Al silicate	377
	4	Contains no Al.		**Wollastonite**	$CaSiO_3$	369
	4	Violet $NaPO_3$ bead.		**Titanite**	$CaTiSiO_5$	412
	4½			**Labradorite**	Ca, Na, Al silicate	352
	4½			**Anorthite**	$CaAl_2(SiO_4)_2$	354
	5	Wet test for Mg.	H_2O in c.t.	**ANTIGORITE**	$H_4Mg_3Si_2O_9$	398
	5	Wet test for Mg.	H_2O in c.t.	**Chrysotile**	$H_4Mg_3Si_2O_9$	400
	Infusible	Wet test for Al.	H_2O in c.t.	**Halloysite**	$H_4Al_2Si_2O_9(H_2O)x$	404
	Infusible	Cu bead tests.	H_2O in c.t.	**CHRYSOCOLLA**	$CuSiO_3\cdot 2H_2O$	405
	Infusible	Ni bed test.	H_2O in c.t.	**Garnierite**	$H_2(Ni,Mg)SiO_4\cdot H_2O$	404
	Infusible	K flame.		**Leucite**	$KAl(SiO_3)_2$	355

SILICATES—*Cont.*

(6) Insoluble or practically so in HCl. (In case of doubt as to solubility it is well to run a blank test with an equal amount of acid, as the acid will give a slight residue.)

2	Li flame.		Lepidolite	$LiKAl(OH)$ silicate	395
2			Glauconite	$KFe(SiO_3)_2 \cdot (H_2O)x$	406
2½	A little H_2O in c.t.		Prehnite	$H_2Ca_2Al_2(SiO_4)_4$	387
2½	Green flame with B flux.		Axinite	$HCa_2(Fe, Mn)Al_2B(SiO_4)_4$	391
3			*GARNET	Ca, Mg, Fe, Al silicate	371
3	Na flame.		Glaucophane	Na, Mg, Al, Fe, OH silicate	367
3			*Vesuvianite	Ca, Al (OH) silicate	378
3			Scapolite	Ca, Na, Al silicate	377
3½	Mn bead tests.		Rhodonite	$MnSiO_3$	362
3½	Li flame.		Spodumene	$LiAl(SiO_3)_2$	370
3½	Green flame with B flux.		TOURMALINE	Mg, Al, B silicate	388
3½	Contains Fe.		*EPIDOTE	$Ca_2(Al, Fe)_3(OH)(SIO_4)_3$	384
	Little or no Fe.		Clinozoisite	$Ca_2Al_3(OH)(SiO_4)_3$	386
3½	H_2O in closed tube.		HORNBLENDE	Ca, Mg, Fe, Al, silicate	365
3½	Violet $NaPO_3$ bead.		Titanite	$CaTiSiO_5$	412
4	Little or no Fe.		Tremolite	$Ca(Mg, Fe_3)(SiO_3)_4$	364
4	Little or no Fe.		Diopside	$Ca(Mg, Fe)(SiO_3)_2$	360
4	Contains Fe.		Augite	Ca, Mg, Fe, Al silicate	361
4½	Can only be distinguished satisfactorily by optical tests.	Plagioclase	Albite	$NaAlSi_3O_8(Ab)$	350
4½			Oligoclase	Ab_9An_1 to Ab_7An_3	351
4½			Andesine	Ab_7An_3 to Ab_1An_1	352
4½			Labradorite	Ab_1An_1 to Ab_3An_7	352
4½			Bytownite	Ab_3An_7 to Ab_1An_9	353

4½	Contains very little Fe.	Micas	Phlogopite	HKMgAl silicate	397
5			MUSCOVITE	$H_2KAl_2(SiO_4)_3$	393
5			Sericite	$H_2KAl_3(SiO_4)_3$	394
5	Contains Fe.		BIOTITE	H, K, Mg, Fe, Al silicate	396
5	Always contains Na.		ORTHOCLASE	$(K, Na)AlSi_3O_8$	344
5	Practically no Na.		Adularia	$KAlSi_3O_8$	346
5	Practically no Na.		Microcline	$KAlSi_3O_8$	347
5			Hypersthene	$(Mg, Fe)SiO_3$	359
5	Green flame with B flux.		*TOURMALINE	Al B silicate	388
5½	May contain H_2O.		Anthophyllite	$(Mg, Fe)SiO_3$	364
5½	No Fe.		TALC	$H_2Mg_3(SiO_3)_4$	400
5½	Fe variable.		CHLORITE	Mg, Fe, Al, OH silicate	397
5½			Beryl	$Be_3Al_2(SiO_3)_6$	368
6	Little or no Fe.		Enstatite	$MgSiO_3$	358
Infusible	Blue with $Co(NO_3)_2$.		Kyanite	Al_2SIO_5	382
	Blue with $Co(NO_3)_2$.		Kaolinite	$H_4Al_2Si_2O_9$	403
	No water in c.t.		QUARTZ	SiO_2	258
	Very little water in c.t.		CHALCEDONY	SiO_2	261
	Much water in c.t.		OPAL	$SiO_2(H_2O)x$	262
	Blue with $Co(NO_3)_2$.		Topaz	$Al_2F_2SiO_4$	380
			Staurolite	$FeAl_5(OH)(SiO_6)_2$	387
	Blue with $Co(NO_3)_2$.		Andalusite	Al_2SiO_5	381
	Blue with $Co(NO_3)_2$.		Sillimanite	Al_2SiO_5	383
	Blue with $Co(NO_3)_2$.		Pyrophyllite	$HAl(SiO_3)_2$	401
			Zircon	Zr_2SiO_4	379

*Means that the mineral is soluble after fusion (alone, not with Na_2CO_3).

Division 4.—Phosphates and Arsenates

The HNO_3 solution of the Na_2CO_3 fusion gives a yellow ppt. with an excess of $(NH_4)_2MoO_4$ solution (with phosphates on gentle heating and with arsenates on boiling.)

	Fusibility	Tests	Mineral	Composition	Page
(*a*) The HNO_3 solution gives a calcium test with dilute H_2SO_4 and alcohol.	5½	No H_2O in c.t.	**APATITE**	$3Ca_3(PO_4)_2 \cdot CaF_2$	313
	5½	H_2O in c.t.	**COLLOPHANE**	$3Ca_3(PO_4)_2 \cdot Ca(CO_3,F_2)(H_2O)_x$	319
	6	A little H_2O in c.t.	**Dahllite**	$3Ca_3(PO_4)_2 \cdot CaCO_3$	315
(*b*) Give tests for Pb.	2	No As mirror in c.t.	**Pyromorphite**	$3Pb_3(PO_4)_2 \cdot PbCl_2$	315
	1½	As mirror in c.t.	**Mimetite**	$3Pb_3(AsO_4)_2 \cdot HCl_2$	316
(*c*) Gives tests for Fe.	2½	H_2O in c.t.	**Vivianite**	$Fe_3(PO_4)_2 \cdot 8H_2O$	318
(*d*) Gives tests for Cu.	Infusible	H_2O in c.t.	**Turquois**	HCuAl phosphate	320

Division 5.—Chromates, Vanadates, and Molybdates

The $NaPO_3$ bead in R.F. is bright green (Note other colors for future use.)

	Fusibility	Tests	Mineral	Composition	Page
(*a*) The $NaPO_3$ bead in O.F. is green.	Infusible		**CHROMITE**	$(Fe,Mg)(Cr,Al)_2O_4$	281
(*b*) The $NaPO_3$ bead in O.F. is yellow.	1½	Pb button on coal.	**Vanadinite**	$3Pb_3(VO_4)_2 \cdot PbCl_2$	317
	2½	H_2O in c.t.	**Carnotite**	$K(UO_2)_2(VO_4)_2 \cdot 8H_2O$	321
(*c*) The $NaPO_3$ bead in O.F. is colorless.	2	Pb button on coal.	**Wulfenite**	$PbMoO_4$	340

Division 6.—Chlorids

The $NaPO_3$ bead saturated with CuO (or malachite) gives a blue flame when heated with the powdered mineral.

	Fusibility	Tests	Mineral	Composition	Page
(*a*) The mineral is soluble in water.	1½	Intense yellow flame.	**HALITE**	NaCl	251
	1½	No H_2O in c.t.	**Sylvite**	KCl	253
	1½	Abundant H_2O in c.t.	**Carnallite**	$KMgCl_3 \cdot 6H_2O$	257
(*b*) The mineral is insoluble in water.	1	Soluble in NH_4OH.	**Cerargyrite**	AgCl	253

Division 7.—Not Previously Included

(Mostly oxids and hydroxids with a few sulfids, fluorids, borates, etc.)

	Fusibility	Tests	Mineral	Composition	Page
(*a*) On coal gives dense white fumes and white sublimate.	Infusible	H_2O in c.t.	Stibiconite	$Sb_2O_4(H_2O)x$	275
(*b*) On coal R.F. gives magnetic particles (Fe).	5½	No H_2O in c.t.	HEMATITE	Fe_2O_3	270
	5½	Little H_2O in c.t.	Turyite	$Fe_2O_3(H_2O)_x$	271
	5½	H_2O in c.t.	LIMONITE	$H_2Fe_2O_4(H_2O)_x$	286
	5½	H_2O in c.t.	Goethite	$Fe_2O_3 \cdot H_2O$	284
(*c*) On coal R.F. gives metallic Cu.	3	No H_2O in c.t.	Cuprite	Cu_2O	267
(*d*) Borax bead tests for Mn.	Infusible	Much H_2O in c.t.	PSILOMELANE	MnO_2, etc $(H_2O)_x$	289
	Infusible	Little H_2O in c.t.	Pyrolusite	$MnO_2(H_2O)_x$	274
	4	No H_2O in c.t.	Wolframite	$(Fe,Mn)WO_4$	338
(*e*) Easily fusible minerals (not previously included).	1	Volatile B.B.	SULFUR	S	217
	1	Soluble in H_2O.	Nitratine	$NaNO_3$	322
	1½	Volatile B.B.	CINNABAR	HgS	234
	1½	Intense yellow flame.	Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	324
	1½	H_3BO_3 in HCl solution.	Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	323
	1½	Intense yellow flame.	Cryolite	Na_3AlF_6	256
	3	HF with H_2SO_4	FLUORITE	CaF_2	254
(*f*) Fusible with difficulty (and not previous included).	5	H_2S odor with HCl.	SPHALERITE	ZnS	231
	5	Yellow residue with HCl.	Scheelite	$CaWO_4$	339
(*g*) Infusible minerals (not previously included.)	Infusible	Blue with $Co(NO_3)_2$: No H_2O in c.t.	CORUNDUM	Al_2O_3	268
		Blue with $Co(NO_3)_2$: No H_2O in c.t.	Spinel	$MgAl_2O_4$	278
		Blue with $Co(NO_3)_2$: H_2O in c.t.	Gibbsite	$Al(OH)_3$	286
		Blue with $Co(NO_3)_2$: H_2O in c.t.	CLIACHITE	$Al_2O_3(H_2O)_x$	287
		Pink with $Co(NO_3)_2$	Brucite	$Mg(OH)_2$	288
		Sn with Zn and HCl.	CASSITERITE	SnO_2	272
		Violet $NaPO_3$ bead	Rutile	TiO_2	273
			Diamond	C	213

B. MINERALS WITH METALLIC OR SUB-METALLIC LUSTER

Division 8.—Sulfids and Sulfo-salts

The Na_2CO_3 fusion made on mica (or platinum) with O.F. stains a moistened silver coin. (Sulfids from previous divison are sphalerite and cinnabar.)

	Fusibility	Tests	Mineral	Composition	Page
(*a*) On coal gives white sublimate far from assay and odor of arsin.	2	Red sublimate in c.t.	**ARSENOPYRITE**	FeAsS	240
	1	Yellow sublimate in c.t.	**Enargite**	Cu_3AsS_4	250
(*b*) On coal gives white sublimate near assay and dense white fumes.	1	Use iodid flux on plaster.	**STIBNITE**	Sb_2S_3	225
	1½	Zn test with $Co(NO_3)_2$.	**TETRAHEDRITE**	Cu Sb, Zn, Fe, etc.	247
	1	Plaster test for Pb.	**Jamesonite**	$Pb_4FeSb_6S_{14}$	245
	1	Ag button on coal.	**Pyrargyrite**	Ag_3SbS_3	246
	1	Ag button on coal.	**Stephanite**	Ag_5SbS_4	248
	1	Ag button on coal.	**Polybasite**	$(Ag,Cu)_{16}Sb_2S_{11}$	249
(*c*) On coal R.F. gives a magnetic residue.	3	S in c.t.	**PYRITE**	FeS_2	236
	3	S in c.t.	**Marcasite**	FeS_2	239
	3	No S in c.t.	**PYRRHOTITE**	$FeS(S)_x$	235
	2	See p. 48 for Ni test.	**Pentlandite**	(Fe,Ni)S	233
	2	Test for Cu.	**CHALCOPYRITE**	$CuFeS_2$	244
	2½	Test for Cu.	**BORNITE**	Cu_5FeS_4	245
	5	Zn test with $Co(NO_3)_2$	**SPHALERITE**	(Zn,Fe)S	231
(*d*) On coal O.F. gives metallic globules.	2	Test for Pb.	**GALENA**	PbS	228
	2½	No S in closed tube	**CHALCOCITE**	Cu_2S	230
	2½	S in closed tube.	**Covellite**	CuS	234
	1	Plaster test for Bi.	**Bismuthinite**	Bi_2S_3	226
	1½	Test for Ag.	**Argentite**	AgS	228
	1	Test for Te.	**Calaverite**	AgTe	242
(*e*) Not previously included.	Infusible	Roasted gives $NaPO_3$ bead test.	**Molybdenite**	MoS_2	227

Division 9.—Not Previously Included

Mostly oxides, hydroxids and native elements.

	Fusibility	Tests	Mineral	Composition	Page
(*a*) On coal gives white sublimate and arsin odor.	2½		Smaltite	$(Co,Ni)As_2$	238
(*b*) On coal R.F. gives magnetic residue.	5½	Red brown streak.	HEMATITE	Fe_2O_3	270
	5½	Red brown streak.	Turyite	$Fe_2O_3(H_2O)_x$	271
	5½	Yellow brown streak.	LIMONITE	$H_2Fe_2O_4(H_2O)_x$	286
	5½	Yellow brown streak	Goethite	$Fe_2O_3 \cdot H_2O$	284
	5½	Strongly magnetic before heating.	MAGNETITE	Fe_3O_4	279
	Infusible	Amethyst borax bead.	Franklinite	$(Zn, Mn)Fe_2O_4$	280
	Infusible	Strongly magnetic before heating.	Iron	Fe	223
	Infusible	Very refractory.	Ilmenite	$FeTiO_3$	310
	3—4	Usually gives Mn test	Wolframite	$(Fe,Mn)WO_4$	338
(*c*) On coal R.F. gives metallic globules.	2	Soluble in HNO_3	SILVER	Ag	220
	2½	Insoluble in HNO_3.	GOLD	(Au,Ag)	218
	3	Blue flame with HCl.	COPPER	Cu_2O	221
	3	Blue flame with HCl.	Cuprite	Cu	267
(*d*) Borax beads tests for Mn.	Infusible	Gives Cl odor in HCl. (H_2O c.t.)	PSILOMELANE	MnO_2, etc. $(H_2O)x$	289
	Infusible		Pyrolusite	$MnO_2(H_2O)x$	274
	Infusible		Manganite	$Mn_2O_3 \cdot H_2O$	285
	Infusible		Hausmannite	Mn_3O_4	282
	4	Reduction color test.	Wolframite	$(Fe,Mn)WO_4$	338
(*e*) Not previously included.	5½	Reduction color test.	Columbite	$(Fe,Mn)(Nb,Ta)_2O_6$	312
		Sn with Zn and HCl.	CASSITERITE	SnO_2	272
		Yellow-green $NaPO_3$ bead.	Pitchblende	$(UO_2)(UO_4)(H_2O)_x$	324
		Soluble in aqua regia.	Platinum	Pt	222
	Infusible	Green borax bead.	CHROMITE	$(Fe,Mg)(Cr,Al)_2O_4$	281
		Violet $NaPO_3$ bead.	Ilmenite	$FeTiO_3$	310
		Violet $NaPO_3$ bead.	Rutile	TiO_2	273
		Negative tests.	GRAPHITE	C	216

BLANK FORM FOR REPORTING MINERALS

Date.....*No*.....*Name*.....

Form.....

Cleavage.....

Luster and color.....

Hardness.....

Streak.....

Spec. Grav.....

Other characters.....

Associates.....*Mineral suspected* _____

Optical characters of crushed fragments.....

.....

.....

Fusibility.....

Flame coloration.....

Closed tube.....

Open tube.....

On charcoal alone.....

On charcoal with Na_2CO_3.....

Borax bead.....

$NaPO_3$ bead.....

Solubility.....

.....

Wet tests.....

.....

Miscellaneous tests.....

.....

.....

.....

.....

Summary of important characters.....

.....*Mineral* _____

*The space in the upper right-hand corner is for a sketch of crystals or crushed fragments.

INDEX AND GLOSSARY

A

A_n. Symbol used for an axis of n-fold symmetry.
Abrasives. Corundum, diamond, diatomite, emery, garnet, quartz.
Absorption, 201
  scheme, 204
Accessory minerals of igneous rocks, 424
Acicular. Needle-shaped.
"Acid" igneous rocks. The same as persilicic rocks, 423
Acids, 8
Acid salt, 10
Actinolite. Ferriferous tremolite.
Acute bisectrix, 193
Adamantine luster, 154
Adjustments of the polarizing microscope, 173
Adularia, 346
Agate. A banded or variegated variety of chalcedony.
Agglomerate, 439
Aggregate polarization. The intricate structure of microcrystalline substances between crossed nicols.
Alabaster. Translucent massive gypsum. Formerly used for onyx marble.
Alaskite, 429
Albite, 350
  twinning, 349
Allotriomorphic. The same as anhedral.
Almandite, 371
Alpha (α). (1) The angle between the b- and c-axes of reference in the triclinic system. (2) The direction of the fastest ray in anisotropic crystals.
Alteration of minerals, 420
Alumina. Aluminum oxid (Al_2O_3).
Aluminates, 277
Aluminum minerals. Alunite, andalusite, cliachite, corundum cryolite, gibbsite, halloysite kaolinite, kyanite, sillimannite, topaz, turquois, and many silicates.
  tests for, 40
Alundum. Artificial Al_2O_3 used as an abrasive.
Alunite, 335
Amazon-stone. The green variety of microcline.
Amber, 415
Amethyst. The purple variety of quartz used as a gem.
Amorphous condition, 54
Amphibole. A group of silicates including anthophyllite, tremolite (actinolite), hornblende, and glaucophane, 363
Amygdaloidal, 426
Analcite, 410
Analyzer, 173
Andalusite, 381

Andesine, 352
Andesite, 433
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Angle, axial, 192
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Anglesite, 329
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ANHYDRITE mineral, 330
rock, 446
Anisotropic, 190
Ankerite. Ferriferous dolomite.
Anomalous optical properties, 206
Anorthite, 354
Anthophyllite, 364
Anthracite, 416
ANTIGORITE, 398
Antimony glance. Synonym of stibnite.
minerals, Jamesonite, polybasite, pyrargyrite, stephanite, stibnite, stibiconite, tetrahedrite. tests for, 41
ocher, Synonym of stibiconite.
A_n. Symbol used for composite symmetry with respect to an axis of n-fold symmetry and a plane normal thereto.
APATITE, 313
Apophyllite, 406
Apparatus, blowpipe, 20
Aquamarine. A transparent sea-green variety of beryl.
Aragonite, 302
Arborescent. Branching like a tree.
Argentite, 228
Arkose, 441
Arsenates, 310
Arsenic minerals. Arsenopyrite, enargite, mimetite, smaltite. tests for, 41
ARSENOPYRITE, 240
Asbestos. Fibrous varieties of tremolite, anthophyllite, or chrysotile.
Asbolite. A soft earthy cobalt-bearing variety of psilomelane.
Asphaltum, 415
Association of minerals, 417
Asterism. A six-rayed star effect produced by symmetrically arranged inclusions in certain minerals.
Asymmetric class. The crystal class devoid of symmetry.
Atomic weights, table of, 6
Auganite, 434
porphyry, 428
Augite, 361
Augitite, 436
Automorphic. The same as euhedral.
Aventurine. A spangled appearance produced by inclusions of hematite, goethite, or mica.
Axes of reference, 73
of symmetry, 60
optic, 191
Axial angle, 192
colors, 202
cross, 85
elements. A collective name used for the axial ratio and the angles between the axes of reference.
plane, 192
ratio, 75
Axinite, 391
Azurite, 307

B

Balance, specific gravity, 149
BARITE, 327

Barium minerals. Barite, witherite.
tests for, 42
Barytes. Synonym of barite.
Basal pinacoid. The pinacoid {001} or {0001}
Basalt, 435
porphyry, 428
Basaltic hornblende. A deep brown variety of hornblende found in volcanic rocks.
Bases, 9
"Basic" igneous rocks. The same as subsilicic rocks, 423
salt, 10
Bastite. Lamellar antigorite pseudomorphous after pyroxene.
Batholith, 426
Bauxite, 442
Baveno twin, 345
Bead tests, 31–32
Becke, Austrian mineralogist (1855–——).
Becke test, 165
Berlin blue. An anomalous interference color of the first-order.
Bertrand lens.
Beryl, 368
Beryllium minerals. Beryl.
tests for, 42
Beta (β). (1) The angle between the a- and c- axes of reference in the monoclinic and triclinic systems. (2) The direction normal to the plane of α and γ in biaxial crystals.
Biaxial, 191.
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Birefringence. The strength of the double refraction.
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Bisilicates. The same as metasilicates $R^{II}SiO_3 = RO.SiO_2$, 343
Bismuth flux. The same as iodid flux, 23
minerals. Bismuthinite.
tests for, 42
Bismuthinite, 226
Bisphenoid, rhombic, 71
tetragonal, 71
Blackband. An impure carbonaceous siderite.
Blackjack. A miner's name for ferriferous sphalerite.
Black opal. A dark-colored precious opal.
Bladed, 128
Blende. Synonym of sphalerite.
Blowpipe, 20
apparatus, 20
reagents, 22
tests, 25
Bluestone. Synonym of chalcanthite.
Bog iron ore. Synonym of limonite.
Bog manganese. Synonym of wad, an impure earthy variety of psilomelane.
Bone-ash (reagent), 23
Bone turquois. An aluminous variety of collophane formed by the replacement of fossil teeth.
Borates, 310
Borax (reagent), 22
bead tests, 31
Boric acid flux, 23
BORNITE, 245
Boron minerals. Axinite, colemanite, datolite, tourmaline, ulexite.
tests for, 42

Bort. Diamond in the form of aggregates without distinct cleavage.
Botryoidal, 128
Bravais. French crystallographer, and physicist (1811–63).
Brazilian twin of quartz. Inversions twins of a right-handed crystal with a left-handed one.
Breccia, 441
Breithaupt, German mineralogist (1791–1873).
Brittle silver ore. Synonym of stephanite.
Brochantite, 332
Bronze mica. Synonym of phlogopite.
Bronzite. Ferriferous variety of enstatite.
Brucite, 288
Brush, American mineralogist (1831–1912).

C

C. Symbol used to indicate that a crystal has a center of symmetry.
Cabochon. The rounded form of cut gem-stones used especially for opal.
Cairngorm. Smoky quartz.
CALAMINE, 376
Calaverite, 242
Calcareous ooze, 444
tufa, 448
Calc-spar. Synonym of calcite.
CALCITE, 291
Calcium minerals. Anhydrite, apatite, aragonite, calcite, clinozoisite, colemanite, collophane, dahllite, dolomite, fluorite, gypsum, scheelite, wollastonite, ulexite, and many silicates.
tests for, 43
Cane sugar, 80
Capillary. Very fine hair-like crystals.
Carbonaceous rocks, 444
Carbonado. A black tough opaque variety of diamond used in diamond drills.
Carbonates, 290
tests for, 43
Carborundum. An artificial silicon carbid (SiC) extensively used as an abrasive.
Carbuncle. Garnet cut in cabochon form.
Carlsbad twin, 345
Carnallite, 257
Carnelian. A clear red chalcedony used as a semi-precious stone.
Carnotite, 321
CASSITERITE, 272
Cat's eye. Gems which exhibit a peculiar reflection because of their fibrous structure.
Celestite, 328
Center of symmetry, 62
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Ceylonite. An iron-bearing variety of spinel.
Chabazite, 410
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CHALCEDONY, 261
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Chalcotrichite. A capillary variety of cuprite.
Chalk, 433
Chalybite. Synonym of siderite.
Charcoal. Use of, as a blowpipe support, 28

Chatoyant. The peculiar optical effect produced by cat's eye.
Chemical composition, 5
compounds, 58
properties, 5
tests, 25
types, 10
Chert, 449
Chessylite. Synonym of azurite, from a locality, Chessy in France.
Chiastolite. A variety of andalusite with symmetrically arranged carbonaceous impurities.
Chile saltpeter. The same as nitratine.
Chlorids, 251
Chlorin, tests for, 44
CHLORITE, 397
Chondrodite, 402
Chondrules. Rounded nodules with excentric fibrous structure characteristic of certain meteorites.
CHROMITE, 281
Chromium minerals. Chromite.
tests for, 44
CHRYSOCOLLA, 405
Chrysolite. Synonym of olivine.
Chrysoprase. An apple-green variety of chalcedony used as a semi-precious stone.
Chrysotile, 400
CINNABAR, 234
Citric acid (reagent), 23
Classification of crystals, 78
of minerals, 212
of ores, 455
of rocks, 422
Clastic. Made up of broken fragments of preexisting rocks.
Clay, 442
Cleavage, 129
CLIACHITE, 287
Clinographic drawing or projection, 85
Clinozoisite, 386
Closed forms, 72
tube tests, 28
Coal, 444
Cobalt minerals. Smaltite.
tests for, 44
Coefficients, 75
Colemanite, 323
Colloform. The rounded, more or less spherical forms assumed by amorphous and metacolloidal minerals in open spaces.
Colloids, 17
COLLOPHANE, 319
Collophanite. Synonym of collophane.
Color of minerals, 154
Colors, interference, 175
Columnar, 128
Columbite, 312
Columbium. Synonym of niobium, one of the chemical elements.
Combination of forms, 55
Complementary forms, 72
Composite crystals, 123
symmetry, 62
Composition-face of a twin crystal, 124
Conchoidal fracture, 131
Concretion, 128
Conglomerate, 441
Congruent forms, 72
Conoscope. A polariscope for convergent light.
Contact goniometer, 57
metamorphism, 453
twins, 124
COPPER, 221

Copper glance. Synonym of chalcocite.
pyrites. Synonym of chalcopyrite.
Copper minerals. Azurite, bornite, brochantite, chalcanthite, chalcocite, chalcopyrite, chrysocolla, copper, covellite, cuprite, enargite, malachite, tetrahedrite.
ores of: bornite, chalcocite, chalcopyrite, copper.
tests for, 45
Cornu, Austrian mineralogist (1882–1909).
Cornuite. An amorphous copper silicate, corresponding to crystalline chrysocolla.
CORUNDUM, 268
Corundum syenite, 431
Covellite, 234
Critical angle, 161
Cristobalite, 264
Crossed nicols, 173
Cryolite, 256
Cryptocrystalline. Apparently amorphous, but made up of very fine interlocking crystals (for example, chalcedony).
Crystal, definition of, 54
drawing, 83
classes, 78
systems, 81
Crystals, classification of, 78
Crystalline aggregates, 128
Crystalline limestone, 452
Crystallites. Minute hair- or fern-like forms found in volcanic glass. They are supposed to represent incipient crystals.
Crystallographic axes. The same as axes of reference.
Crystallography. The science relating to crystals in all aspects, often erroneously used for geometrical crystallography.
Cube, 90
Cupellation, silver, 34
Cuprite, 267
Curve of hardness, 154
Cyanite. Variant of kyanite, 382
Cyclic twin, 124

D

Dacite, 432
Dahllite, 315
Dana, American geologist and mineralogist (1813–1895).
Datolite, 391
Decrepitate. To fly to pieces when heated.
Dedolomitization, 453
Deltohedron, 94
Dendritic. Branching like a tree.
Dense igneous rocks, 427
Determination of minerals, 463
Devitrification. The gradual change of glass to crystalline aggregates.
Diabase, 435
Diallage. A lamellar variety of diopside.
Diamond, 213
Diatomaceous earth. A synonym of diatomite.
Diatomite, 444
Dichroic, 202
Dichroscope, 201
Dihexagonal bipyramid class, 102
pyramidal class, 80
Dike, 426
Dimorphism. The particular case of polymorphism in which there are two polymorphs.
Diopside, 360

Diorite, 433
Diploid, 96
Diploidal class, 95
Dispersion. The divergence of the optical constants for different parts of the spectrum.
Disseminated. Scattered through a rock or vein in small quantities.
Disthene. Synonym of kyanite.
Ditetragonal bipyramidal class, 98
prism, 69
pyramidal class, 80
Ditrigonal bipyramidal class, 80
prism, 69
pyramidal class, 107
Dodecahedron, 90
Dodecants. The twelve divisions into which space is divided by the four axes of reference of the hexagonal system.
Dog-tooth spar. A variety of sharp-pointed calcite crystals.
DOLOMITE, 296
Dolomitic limestone, 449
Dolomitization, 449
Domatic class. The crystal class with a single plane of symmetry, 80
Dome, 69
Double refraction, 169
Drusy. Apparently sprinkled over with minute crystals.
Dry-bone. A local synonym of smithsonite (Wis.) or cerussite (Mo.)
Drawing of crystals, 83
Dunite, 436

E

Eclogite. A metamorphic rock with garnet and either a pyroxene or an amphibole.
Edge of a crystal, 55
Effervescence. The bubbling caused by the evolution of gas such as CO_2.
Efflorescent. Gives up its water of crystallization on standing.
Elæolite. A synonym of nepheline or nephelite.
Elastic. An elastic mineral springs back when bent in contrast to a flexible mineral which remains bent.
Electrum. A naturally occurring alloy of gold or silver with over 20 per cent. of silver.
Elements, axial. A collective name used for the axial ratio and the angles between the axes of reference.
list of chemical, 6
occurrence of chemical, 6
of symmetry, 63
Ellipse, optic, 189
Ellipsoid, optic, 189
Emerald. The clear green variety of beryl used as a gem.
Emery. A mixture of corundum with magnetite.
Enantiomorphous, 72
Enargite, 250
Enstatite, 358
EPIDOTE, 384
Equant. The same as equidimensional.
Erubescite. A synonym of bornite.
Essonite (Hessonite). A variety of grossularite garnet used as a gem.
Etch-figures, 66
Ether, 156
Euhedral, 54
Exfoliate. To swell up or spread out like the leaves of a book.

Extinction, 184
angle, 185
direction, 184
Extraordinary ray, 169
Extrusive (igneous) rocks, 426

F

Fabric, 425
Face, crystal, 55
Face color. The color of a crystal when viewed in a certain direction.
-symbol, 76
Facet, 55
Fahlore. A synonym of tetrahedrite.
Faster ray, 187
Fedorov, a Russian crystallographer.
Feldspars, 344
Feldspathoids, 354
Felsitic. The fine grained texture of volcanic rocks without phenocrysts.
Ferberite. The iron end-member of the wolframite series.
Ferromagnesian, 424
Fertilizers, minerals used as: carnallite, collophane, kainite, nitratine, sylvite.
Fire-opal. Opal with fire-like reflections.
Flame, oxidizing, 25
reducing, 26
tests, 26
Flexible. See elastic.
Flint. A massive chalcedony rock, practically the same as chert.
Fluorids, 251
Fluorin, tests for, 45
Fluorescence, 255
FLUORITE, 254
Fluor spar. A synonym of fluorite.
Foliated. Made up of flat plates.
Fool's gold. A synonym of pyrite.
Form, 68
closed, 72
general, 79
limit, 79
open, 72
-symbol, 76
Formula, determination of, of a mineral, 11
weight. The sum of the atomic weights of the atoms of a chemical compound.
Forsterite, 374
Fowlerite. A zinc-bearing variety of rhodonite.
Fracture, 131
Franklinite, 280
Freibergite. A silver-bearing tetrahedrite.
French chalk. A variety of talc used by tailors.
Friable. Capable of being pulverized by rubbing between the fingers.
Friedel, G., French crystallographer and mineralogist. (1865———).
Fusibility, scale of, 34

G

Gabbro, 434
porphyry, 434
GALENA, 228
Galenite. A synonym of galena.
Gamma (γ). A Greek letter used (1) for the angle between the a- and b-axes of reference in the triclinic system and (2) for the direction of the slowest ray in anisotropic crystals.
Gangue. The non-metallic part of a vein.
minerals, 456

Garnierite, 404
Gel, 17
Gelatinization, 495
Gems. Diamond, emerald, ruby, sapphire, etc.
General form, 79
Geode, 128
Geometrical crystallography, 54
Geyserite. A variety of opal formed in hot springs.
Gibbsite, 286
Gilsonite, 415
Glance. An abbreviation of copper glance (chalcocite).
Glass, 413
Glauconite, 406
Glaucophane, 367
Glide-plane of symmetry, 138
Gliding, 131
Gneiss, 451
Goethite, 284
GOLD, 218
Gold minerals. Calaverite, gold.
tests for, 45
Goniometer, contact, 57
reflection, 57
Gossan, 459
Grained igneous rocks, 427
Granite, 429
porphyry, 430
Granitic or granitoid. The texture of even-grained igneous rocks such as granite.
Granodiorite, 432
Graphic determination of indices and axial ratios: 97, 101, 111, 115, 120, 123.
granite. An intergrowth of quartz and orthoclase or microcline.
texture. The texture like that of graphic granite.
GRAPHITE, 216
Gray copper. A synonym of tetrahedrite.
Graywacke, 441
Greisen. A quartz-muscovite rock formed by high-temperature hydrothermal solutions.
Greensand, 441
Greenstone.
Grossularite, 371
Groth, German crystallographer (1843———).
Groundmass, 425
Gypsite, 446
GYPSUM (mineral), 332
(rock), 445
wedge. A thin wedge-shaped slice of selenite.
Gyroid. A 24-faced form with the symmetry $6A_2 \cdot 4A_3 \cdot 3A_4$.
Gyroidal class, 80

H

Habit, crystal. The general shape of a crystal determined by growth in certain directions.
Hackly, 131
HALITE, 251
Halloysite, 404
Haloids, 251
Hardness, scale of, 153
Hausmannite, 282
Haüy, R. J. French mineralogist and physicist. The founder of the science of geometrical crystallography (1743–1822).
Heavy liquids, 150
Heavy spar. A synonym of barite.
HEMATITE, 270
Hematite, brown. A synonym of limonite.

Hemihedral, 83
Hemimorphic. Crystals in which the two ends are differently terminated.
Hemimorphite. A synonym of calamine.
Hessel. German mineralogist (1796–1872).
Heulandite, 408
Hexagonal bipyramidal class, 80
pyramidal class, 80
scalenohedral class, 104
system, 102
trapezohedral class, 80
Hexahedron. Synonym of a cube.
Hexoctahedral class, 90
Hexoctahedron, 91
Hextetrahedral class, 93
Hextetrahedron, 94
Hiddenite. An emerald-green variety of spodumene used as a gem.
Hintze, German mineralogist (1851–1916).
Holohedral, 83
Holosymmetric, 83
HORNBLENDE, 365
Hornblendite. An igneous rock consisting essentially of hornblende.
Hornfels, 454
Horn silver. A synonym of cerargyrite.
Horse-flesh ore. A synonym of bornite.
Hübnerite. The manganese end-member of the wolframite group.
Hue, 155
Hyacinth. A variety of zircon used as a gem.
Hyalite. A clear, colorless, colloform variety of opal.
Hydrargillite. A synonym of gibbsite.
Hydrion. The element H in an acid salt.
Hydrocarbons, 414
tests for, 44
Hydrochloric acid (reagent), 23
Hydrogel, 18
Hydromagnesite, 308
Hydrothermal metamorphism, 454
Hydrous salts, 11
Hydroxids, 284
Hydroxyl. The radical or ion (OH).
Hypersthene, 359
Hypogene, 461

I

Ice (mineral), 266
(rock), 449
Iceland spar. The clear transparent variety of cleavable calcite.
Ideal form. A crystal form or combination in which like faces are of the same shape and size.
Idocrase. A synonym of vesuvianite.
Igneous rocks, 422
Ilmenite, 310
Imitative forms, 128
Index of refraction, 159
Indicatrix. A synonym of the optic ellipsoid.
Indices, Miller, 75
of refraction, 159
Indigo copper. A synonym of covellite.
Injected rocks, 426
Intercepts, 73
Interfacial angle, 56
Interference, 175
colors, 175
of light, 175

Interference figures, 193
color chart, 180, 181, 183
Intergrowth. An interlocking arrangement of two substances produced by simultaneous crystallization.
Internal structure of crystals, 132
Intrusive, 426
Intumesce, 34
Inversion, 62
twin, 124
Iodid flux, 23
Iridescence. A rainbow effect produced by the interference of light in thin surface films.
Iron, 223
minerals. Arsenopyrite, bornite, chalcopyrite, chromite, columbite, franklinite, goethite, hematite, ilmenite, iron, jarosite, limonite, magnetite, marcasite, pyrite, pyrrhotite, siderite, turyite, vivianite, wolframite, and some silicates.
tests for, 46
pyrites. A synonym of pyrite.
Isodimorphism, 290
Isometric system, 89
Isomorphism, 14
Isomorphous mixtures, 16
Isotropic, 190

J

Jade. A tough compact green or greenish-white ornamental stone consisting either of an amphibole (nephrite) or of a pyroxene (jadeite).
Jamesonite, 245
Jargon. A pale-colored variety of zircon used as a gem.
Jarosite, 336
Jasper. A red to yellow or brown variety of chalcedony colored by iron oxids.
Jolly balance. A specific gravity balance in which use is made of a spiral brass wire.

K

Kainite, 331
Kaolin. Impure kaolinite.
Kaolinite, 403
Kaolinization. The process by which kaolinite is formed.
Kidney ore. A reniform variety of hematite from England.
Kunzite. A transparent lilac-colored variety of spodumene used as a gem.
Kyanite, 382

L

Labradorite, 352
Laccolith, 426
Lamellar, 128
Lampadite. A cupriferous variety of psilomelane.
Lapilli, 439
Lapis lazuli. A mixture of lazurite, calcite, diopside, etc.
Latite, 432
Law of constancy of interfacial angles, 64
of rational indices, 74
of rational symmetric intercepts, 74
Lazurite, 357
Lead minerals. Anglesite, cerussite, galena, jamesonite, mimetite, pyromorphite, vanadinite, wulfenite.
tests for, 47

Left-handed quartz crystal, 260
Lenticular. Lens-shaped.
Lepidolite, 395
Leucite, 355
Light, convergent, 193
nature of, 156
polarized, 107
Limburgite, 436
Lime. Calcium oxid (CaO), often incorrectly used for calcium carbonate.
Limestone, crystalline, 452
oölitic, 448
sedimentary, 442
Limit form, 79
LIMONITE, 286
Lindgren, American geologist (1860–——).
Linear projection, 88
Lithia. Lithium oxid (Li_2O).
Lithium minerals. Lepidolite, spodumene.
tests for, 47
Lodestone. A variety of magnetite which acts as a magnet.
Luster, 154

M

Macle. Synonym of a twin-crystal.
Macroscopic. The same as megascopic.
Magma, 424
Magnesia. Magnesium oxid (MgO)
Magnesian limestone. Limestones containing magnesium, but in quantities insufficient for dolomite.
Magnesite, 298
Magnesium minerals. Antigorite, anthophyllite, brucite, carnallite, chondrodite, chrysotile, dolomite, enstatite, forsterite, hydromagnesite, kainite, magnesite, olivine, spinel, talc, tremolite, and other silicates.
tests for, 47
Magnetic iron ore. A synonym of magnetite.
pyrites. A synonym of pyrrhotite.
MAGNETITE, 279
MALACHITE, 307
Malleable. Capable of being hammered out flat.
Maltha, 414
Mammillary, 128
Manebach twin, 345
Manganese minerals. Franklinite, hausmannite, manganite, pyrolusite, psilomelane, rhodochrosite, rhodonite.
tests for, 47
Manganite, 285
Marble. Any limestone that will take a good polish, but also used by some for a metamorphic limestone.
Marcasite, 239
Martite. A pseudomorph of hematite (or turyite) after magnetite.
Massive. Without definite form or structure.
Measurement, of axial angle, 199
of crystals, 56
of index of refraction, 161
of interfacial angles, 56
Mechanically formed sedimentary rocks, 439
Mediosilicic igneous rocks, 423
Megascopic. Capable of being seen with the unaided eye in contrast with microscopic.
Melanite. A titaniferous variety of andradite.

Menaccanite. A synonym of ilmenite.
Mercury minerals. Cinnabar.
tests for, 47
Metacolloids. Microcrystalline substances of colloidal origin.
Metamorphic rocks, 450
Metamorphism, 450
Metasilicates, 343
Metasomatic replacement. The replacement of a rock mass by solutions.
Methylene iodid, 150
Miarolitic. A term applied to the structure of injected rocks containing cavities, lined with euhedral crystals.
Micaceous, 128
Mica group, 392
plate, 188
Microchemical gypsum test, 43
Microcline, 347
Microcosmic salt. The same as salt of phosphorus or acid sodium ammonium phosphate used in blowpipe analysis.
Microlites. Minute crystals found in volcanic glasses.
Microperthite. Perthite on a small scale.
Microscope, polarizing, 172
Miller, W. H., English crystallographer and mineralogist (1801–1880).
Miller indices, 75
Mimetic twinning. The tendency of twinning to raise apparently the grade of symmetry and thus imitate other crystals.
Mimetite, 316
Mineral, definition of, 1
Mineraloid, definition of, 413
Mispickel. A synonym of arsenopyrite.
Molecular compounds, 10–11
Molybdates, 338
Molybdenite, 227
Molybdenum minerals. Molybdenite, wulfenite.
tests for, 48
Monochromatic light, 158
Monoclinic system, 115
Monzonite, 431
Moonstone. A variety of adularia with a pearly reflection, used as a gem.
Morganite. A pink variety of beryl, used as a gem.
Morphological properties, 54
Morphology, crystal. That portion of crystallography which deals with the form and internal structure of crystals.
Mountain cork, leather. } Varieties of tremolite.
Mundic. A local name for pyrite or marcasite.
MUSCOVITE, 393

N

n. A symbol used for the index of refraction.
Native copper, 221
elements, 213
gold, 218
iron, 223
platinum, 222
silver, 220
Natrolite, 411
Negative crystal. A cavity within a crystal which has the characteristic shape of the crystal itself.
elongation, 189
optically, 190

Nepheline, 355
Nepheline syenite, 431
Nephelite. A synonym of nepheline.
Nephelite syenite. A synonym of nepheline syenite.
Nickel minerals. Garrierite, peutlandite.
tests for, 48
Nicol. The same as a nicol prism.
Nicol prism, 171
Niobates, 312
Niobium minerals. Columbite.
tests for, 48
Niter. Potassium nitrate, KNO_3.
Nitrates, 310
tests for, 48
Nitratine, 322
Nitric acid (reagent), 23
Nodular, 128
Non-metallic luster. Any luster but metallic.
Nontronite. The iron analogue of kaolinite.
Normal salts, 10
Norite, 434
Notation of crystal faces, 73

O

Oblique extinction, 184
Obsidian, 430
Obtuse bisectrix, 193
Obtuse rhombohedron, 105
Occurrence of minerals, 417
Ocher. A clay colored by iron oxids.
Octahedron, 90
Ocular of microscope. The same as the eye-piece.
Oligoclase, 351
Oil shale, 416
OLIVINE, 373
Olivine gabbro, 435
diabase. A diabase containing olivine.
Omphacite. A bright green variety of diopside characteristic of eclogites.
Onyx. A variety of chalcedony with sharply contrasted bands of colors.
Onyx marble. A banded variety of calcite or aragonite formed by water solutions.
Onyx, Mexican. The same as onyx marble.
Oöids. The individual spheres of an oölitic rock.
Oölite. A rock made up of minute spheres formed by concretionary action.
Oölitic limestone, 448
structure. The structure of an oölite.
OPAL, 262
Opalescence. The peculiar milky appearance often seen in opal.
Opalized wood. A replacement of wood by opal.
Open form, 72
Open tube tests, 27
Ophicalcite, 455
Optical anomalies, 206
character, 190
constants, 192
orientation, 207
properties, 156
tests, 204
Optic axes, 191
axis. The *c*-axis of reference in the tetragonal and hexagonal systems.
ellipse, 189
ellipsoid, 189

Optic normal, 191
Optics, crystal. Optical crystallography or the branch of crystallography that deals with the transmission of light in crystals.
Order of succession, 418
Ordinary ray, 169
Ores, 456
Organically-derived sedimentary rocks, 442
Oriental amethyst. A purple variety of corundum.
emerald. A green variety of corundum.
ruby. The true ruby, a variety of corundum.
sapphire. The true sapphire, a variety of corundum.
topaz. A yellow variety of corundum.
Orientation of a crystal. The placing of a crystal in its conventional position with the *c*-axis vertical and the *a*-axis pointing toward the observer.
optical, 207
Origin of minerals, 417
Ortho-axis. The *b*-axis in the monoclinic system.
Orthographic drawing or projection, 84
Orthorhombic system, 111
ORTHOCLASE, 344
Orthosilicates, 343
Oxidizing flame, 25
Oxids, 258
Ozocerite, 415

P

P. Symbol used for plane of symmetry.
Parageneses, 418
Parallel growth, 123
Parameters. The relative intercepts of the unit face (111) on the axes of reference.
Paramorph, 424
Parting, 131
Path difference, 176
Peacock copper. Tarnished chalcopyrite.
Pearl-spar. A synonym of dolomite.
Pearly luster, 154
Pediad class. The asymmetric crystal class, in which the general form is a pedion.
Pedion, 69
Pegmatites, 437
Penetration twin, 124
Penfield. American mineralogist (1856–1906).
Pentagonal dodecahedron. A synonym of pyritohedron.
Pentlandite, 233
Percussion-figure, 392
Pericline. A variety of albite elongated in the direction of the *b*-axis.
Pericline twin-law. The twin-law for plagioclase feldspars in which the *b*-axis is the twin axis, 349
Peridot. A gem variety of olivine.
Peridotite, 436
Perlite, 430
Persilicic igneous rocks, 423
Perthite. An intergrowth of microcline and albite, 348
Petrifaction. The replacement of fossils by mineral substances, 421
Petrographic microscope, 172
Petrography. The science which treats of rocks, especially from the descriptive side.

Petroleum, 414
Petrology. The study of rocks from a broad geological standpoint.
Phantom crystal. A crystal in which an earlier stage of growth is marked by a color difference or a row of inclusions.
Phase, 158
Phenocryst, 425
Phlogopite, 397
Phonolite, 432
Phosphates, 310
tests for, 49
Phosphate rock. A synonym of phosphorite.
Phosphorite, 450
Physical properties, 147
Picotite. A chromium-bearing variety of spinel.
Piezoelectric. The property of developing electricity by changes in pressure exerted upon a crystal.
Pinacoid, 69
Pinacoidal class, 121
Pisolitic. Made up of spheres the size of buck-shot or larger which have been formed by concretionary action.
Pistazite. A synonym of epidote.
Pitchblende, 324
Pitchstone, 430
PLAGIOCLASE, 348
Plaster tablets, 21
tests on, 30
Platinum, 222
tests for, 49
Pleochroism, 201
Pleonaste. An iron-bearing variety of spinel.
Plumose. Feather-like.
Plutonic rocks. Deep-seated igneous rocks as contrasted with the volcanic or surface igneous rocks.
Point-systems, 138
Polar axis. An axis of symmetry which has different faces at opposite ends.
edges. Edges that intersect the *c*-axis.
Polariscope, 193
Polarized light, 167
Polarizer, 173
Polarizing microscope, 172
Polybasite, 249
Polymorphism, 18
Polysilicates, 343
Polysynthetic twin, 236
Porodine, 17
Porphyritic, 425
Porphyry. An igneous rock with a porphyritic texture.
Positive elongation, 189
optically, 190
Potash feldspar. Either orthoclase or microcline.
Potassa. Potassium oxid (K_2O).
Potassium minerals. Adularia, alunite, biotite, carnallite, jarosite, kainite, lepidolite, leucite, microcline, muscovite, orthoclase, sylvite.
tests for, 49
Precious opal. A variety of opal with a play of colors and used as a gem.
stones. Diamond, emerald, ruby, and sapphire. Other stones used as gems are called semi-precious.
Prehnite, 387
Primary, 460

Primitive form. A crystal form from which other forms may be derived.
Principal axis. The *c*-axis of reference (A_2, A_4, or A_6) in the tetragonal and hexagonal systems.
Prism, 69
Prismatic class, 116
habit, 469
Projection, clinographic, 85
linear, 88
orthographic, 84
Proustite. The arsenic analogue of pyrargyrite.
Pseudohexagonal. Orthorhombic or monoclinic crystals which simulate crystals of the hexagonal system.
Pseudomorph, 421
PSILOMELANE, 289
Pumice, 430
Pycnometer, 150
Pyramid, 69
Pyramidal habit, 469
Pyrargyrite, 246
PYRITE, 236
Pyrites. A synonym of pyrite.
Pyritohedron, 95
Pyroclastic rocks, 438
Pyroelectric, 389
Pyrognostic tests. Blowpipe tests, 25
Pyrolusite, 274
Pyromorphite, 315
Pyrope, 371
Pyrophyllite, 401
PYROXENE, 359
group, 357
Pyroxenite, 436
PYRRHOTITE, 235

Q

Qualitative scheme, 39
Quarter-undulation mica plate, 188
QUARTZ, 258
wedge, 199
Quartzite, 452
Quartz monzonite. A quartz-bearing monzonite.
porphyry. An altered, devitrified rhyolite or rhyolite porphyry.

R

R. A general symbol standing for some metal.
Radical. A group of chemical elements which act as a unit such as NH_4 or SO_4.
Rare-earth metals. Cerium, erbium, lanthanum, neodidymium, prascodidymium, thorium, and yttrium.
Rational indices, 74
Ray of light, 158
Reagents, 22–25
Reduction color tests, 33
Reducing flame, 26
Reflection goniometer, 57
total, 161
twins, 123
Refraction of light, 159
index of, 159
indices of, table of, 207–209
Refractometer, 163
Regional metamorphism, 451
Regular system. The same as the isometric system.
Relief, 167
Reniform, 128

Replacement, 420
Residual minerals, 440
Resinous. The luster of resin.
Resins, 414
Reticulate. Made up of a net-work.
Rhodochrosite, 300
Rhodonite, 362
Rhombic bipyramid, 69
bipyramidal class, 112
bisphenoid, 71
bisphenoidal class, 80
dodecahedron, 90
prism, 69
prismatic class. The same as the prismatic class.
pyramid, 69
pyramidal class, 80
section of plagioclase crystals, 350
Rhombohedral carbonates, 290–301
class, 80
subsystem, 102
Rhombohedron, 71
Rhyolite, 430
porphyry, 430
Right-handed quartz crystal, 260
Rock crystal. The clear transparent variety of quartz used for ornamental purposes and in optical and piezoelectric work.
Rocks, 422
, igneous, 422
, metamorphic, 450
, sedimentary, 439
Rock-forming minerals, 424
Rock-salt, 446
Rotation twins, 123
Rotatory-reflection. The simultaneous operations of reflection and rotation.
Rubellite. The pink to red variety of tourmaline.
Ruby. The transparent red variety of corundum.
copper. A synonym of cuprite.
silver. A group name for pyrargyrite and proustite.
Rutile, 273

S

Saline residues, 447
Salt. (1) Synonym of halite. (2) compounds formed by the union of bases with acids.
Salt of phosphorus. Hydrous acid sodium ammonium phosphate used in bead tests.
Salts, acid, 10
basic, 10
normal, 10
Sand, 440
Sandstone, 441
Sanidine. A clear transparent variety of orthoclase found in volcanic igneous rocks.
Sapphire. The transparent blue variety of corundum.
Sard. A brownish-red variety of chalcedony used as a gem.
Sardonyx. Agate with red and white bands.
Satin-spar. A fibrous variety of gypsum.
Scalar, 147
Scalenohedral, hexagonal, class, 104
tetragonal, class, 80
Scalenohedron. There are two kinds of scalenohedrons but when no qualifying term is used the hexagonal scalenohedron is meant.
Scalenohedron, hexagonal, 71
tetragonal, 71

Scale of fusibility, 34
hardness, 153
Scapolite, 377
Scheelite, 339
Schistose. With the characters of a schist.
Schists, 451
Schoenflies, German mathematician (1853– ——).
Schorl. An old name for tourmaline.
Sclerometer, 154
Screw-axis of symmetry, 138
Secondary, 460
enrichment, 460
Sectile. Capable of being cut by a knife but not flattened out by a hammer.
Sedimentary rocks, 439
Selenite. The cleavable variety of gypsum.
Selenite plate. A plate of selenite showing the sensitive tint (*q.v.*).
Semi-opal. Common opal as distinguished from precious opal and fire opal.
Sensitive tint. The purple interference color between red of the first-order and blue of the second-order, 185
Sericite, 394
Serpentine (rock), 455
minerals of. Antigorite, chrysotile.
Serpentinization. The alteration of peridotite to serpentine.
Shade, 155
Shale, 442
SIDERITE, 299
Silica minerals, stability relations of, 265
Silicates, 341
Siliceous sinter, 449
Sill, 426
Sillimanite, 383
SILVER, 220
assay, 34
cupellation, 34
glance. A synonym of argentite.
minerals of. Argentite, cerargyrite, polybasite, pyrargyrite, silver, stephanite.
tests for, 50
Skeleton crystals. More or less hollow crystals formed by rapid crystallization.
Slate, 451
Slower ray, 187
Smaltite, 238
SMITHSONITE, 301
Smoky quartz. A variety of quartz with a brown pigment.
Snow, 266
Soapstone. A massive metamorphic rock consisting essentially of talc.
Soda. Sodium oxid (Na_2O). This term is often incorrectly used for sodium carbonate.
Soda-lime feldspar. A synonym for plagioclase.
Sodalite, 356
Soda niter. A synonym of nitratine.
Sodium carbonate bead tests, 33
metaphosphate bead tests, 32
minerals. Albite, analcite, cryolite, glaucophane, halite, hazurite, natrolite, nepheline, nitratine, sodalite, ulexite, scapolite.
tests for, 50
Sohncke, German mathematician (1842– ——).
Solid solutions, 16

Solubility of minerals, 38
Solutions, solid, 16
Space-groups, 139
Space-lattice, 132
Specific gravity, 148
Specific gravity balance, 149
Specular iron-ore. A synonym of hematite.
SPHALERITE, 231
Spherulites, 128
Sphene. A synonym of titanite.
Sphenoid, 69
Sphenoidal class, 80
Spinel, 278
Spodumene, 370
Stalactitic, 128
Staurolite, 387
Steatite. The same as soapstone.
Stellate. With a radiate star effect.
Steno. A Danish scientist, who first discovered the law of constancy of interfacial angles (1638–1687).
Stephanite, 248
Stibiconite, 275
STIBNITE, 225
Stilbite, 409
Streak, 155
Streak-plate, 155
Stream-tin. A variety of cassiterite found in placer deposits.
Striations, oscillatory. Striations produced by alternate development of two adjacent forms. twinning, 125
Strontianite, 304
Strontium, minerals of. Celestite, strontianite.
tests for, 51
Structure, internal, of crystals, 132
of minerals, 128
of igneous rocks, 425
Sub-. A prefix indicating a lower quality or degree than the normal.
Subhedral, 54
Subjacent, 426
Sublimates on charcoal, 29
in closed tube, 28
in open tube, 27
on plaster, 30
Submetallic. With a luster intermediate between metallic and adamantine.
Subsectile. Imperfectly sectile like chalcocite.
Subsilicates. Silicates of the type n RO·SiO_2 where $n > 2$, 343
Subsilicic, 423
Succession, order of, of minerals, 418
Sulfantimonates, 243
Sulfantimonites, 243
Sulfarsenates, 243
Sulfarsenites, 243
Sulfates, 326
tests for, 51
Sulfids, 225
tests for, 51
Sulfo-acids, 9
Sulfoferrites, 243
Sulfo-salts, 243
SULFUR, 217
Sulfuric acid (reagent), 23
Sunstone. A variety of oligoclase with a spangled appearance due to inclusions of hematite or goethite.
Supergene, 461
enrichment, 460
Surficial. Deposits found on the immediate surface of the earth.
Syenite, 431
porphyry, 431
Sylvite, 253

Symbols of crystal faces, 74
Symmetry, 60
Symmetry, axis of, 60
center of, 62
composite 62
plane of, 61
Symmetrical extinction, 184
Synthesis of minerals, 418
Systems, crystal, 81

T

Table, of the 32 crystal classes, 80
of atomic weights, 6–7
Tables, determinative, 466
indices of refraction, 207–209
specific gravity, 150–152
Tabular habit, 468
TALC, 400
Talc schist, 451
Tarnish. A thin surface film caused by oxidation.
Tellurids, 242
Tellurium, minerals of. Calaverite.
tests for, 52
Test-plates, 188
Tetartohedral, 83
Tetartoid. The twelve-faced general form of the tetartoidal class.
Tetartoidal class, 80
Tetragonal bipyramidal class, 80
bisphenoidal class, 80
pyramidal class, 80
scalenohedral class, 80
system, 97
trapezohedral class, 80
TETRAHEDRITE, 247
Tetrahedron, 94
Tetrahexahedron, 91
Texture of igneous rocks, 424
Thin-section. A paper-thin slice of a mineral or rock, used for microscopic examination and optical tests.
Tin minerals. Cassiterite.
tests for, 52
Tin-stone. A synonym of cassiterite.
Tin-stone veins, 457
Tint, 155
Titanite, 412
Titanium minerals. Ilmenite, rutile, titanite.
tests for, 52
Topaz, 380
Total reflection, 161
Touchstone. A black variety of chalcedony used for testing the purity of gold and other metals. The color and solubility of the streak are tested.
TOURMALINE, 388
Trachyte, 431
Trachyte porphyry
Translation, 136
Trap. A dense black igneous rock, usually basalt or diabase.
Trapezohedron, 91
hexagonal, 71
tetragonal, 71
trigonal, 71
Travertine, 448
Tremolite, 364
Trichroic, 202
Triclinic system, 121
Tridymite, 263
Trigonal bipyramid, 70
bipyramidal class, 80
prism, 68
pyramid, 70
pyramidal class, 80
trapezohedron, 71
trapezohedral class, 109
Trimorphism. The particular case

of polymorphism in which there are three polymorphs.
Trisoctahedron, 91
Tris etrahedron, 94
Troostite. A manganese-bearing variety of willemite.
Truncation. The modification of an edge of a crystal by a face that makes equal angles with adjacent faces.
Tufa, calcareous, 448
Tuff, 439
Turgite. The same as turyite.
Tungstates, 338
Tungsten minerals. Scheelite, wolframite.
tests for, 53
Turkey-fat ore. A yellow variety of smithsonite containing CdS in solid solution.
Turmeric paper. Paper saturated with a solution of turmeric and used for testing borates and zirconium.
Turquois, 320
Turyite, 271
Twin-axis, 123
-crystals, 123
-law, 124
-plane, 123
-seam, 125
Twinning striations, 125
Type symbols, 75
Types chemical, 10

U

Ulexite, 324
Ultrabasic rocks, 437
Uniaxial, 190
Unisilicates. The same as orthosilicates. $R^{II}_2SiO_4 = 2R''O{\cdot}SiO_2$, 343
Unit bipyramid. The form {111} or $\{10\bar{1}1\}$.
face, 75
forms. The forms {110}, {101}, {011}, and {111}.
prism. The form {110}.
pyramid. The form {111} or $\{10\bar{1}1\}$.
rhombohedron. The rhombohedron, $\{10\bar{1}1\}$.
series of bipyramids, 113
Uralite. An actinolite pseudomorph after, or alteration of, pyroxene.
Uralitization. The alteration involved in the formation of uralite.
Uraninite. The crystalline equivalent of pitchblende.
Uranium minerals. Carnotite, pitchblende.
tests for, 53

V

Valencianite. A synonym of adularia.
Vanadates, 317, 321
Vanadinite, 317
Vanadium minerals. Carnotite vanadinite.
tests for, 53
Variations in the chemical composition of minerals, 4
Vectorial, 147
Veins, 455
minerals of, 456
Verd antique. A serpentine rock veined or mottled with carbonates.
Vertices of a crystal, 55
Vesicular, 425
Vesuvianite, 378

Vibration directions, 184
plane of, 167
Vicinal faces. Crystal faces with high indices which adjoin or replace faces with lower indices.
Vitreous luster, 154
Vitrophyre, 430
Vivianite, 318
Volcanic ash, 439
bombs, 439
breccia. Practically the same as an agglomerate.
dust, 439
emanations, 437
rocks, 426
tuff, 439
Vug. A cavity in a vein lined with crystals.

W

Water of constitution, 11
of crystallization, 11
tests for, 46
Wave-front, 158
-length, 158
-motion, 156
Weathering, 440
Wedge, gypsum, 206
quartz, 199
Weiss. German crystallographer (1780–1856).
Weiss symbols, 75
Wernerite. The most prominent member of the scapolite group.
Whewellite. Naturally occurring hydrous calcium oxalate, 416
Willemite, 375
Witherite, 305
Wolframite, 338
Wollaston. An English chemist who invented the reflection goniometer (1766 – 1828).
Wollastonite, 369
Wood-opal. The same as opalized wood.
Wood, silicified. Wood replaced by chalcedony, opal, or quartz.
Wulfenite, 340

X

X-rays and crystal structure, 132
X-ray spectrometer, 141

Z

ZEOLITE (group), 407
Zinc blende. A synonym of sphalerite.
minerals. Calamine, franklinite, smithsonite, sphalerite, willemite.
tests for, 53
Zircon, 379
Zirconium minerals. Zircon.
tests for, 53
Zone of crystal faces, 56
Zone of oxidation, 459
Zone of secondary enrichment, 460